# INTELLIGENT ROBOTS

## CHAPTER 0: INTRODUCTION

# Contact Information

**Instructor**: Qi Hao

**E-mail**: hao.q@sustc.edu.cn

**Office**: Nanshan iPark A7 Room 906

**Office Hours**: M 2:00-4:00pm

Available other times by appointment or the open door policy

**Office Phone**: (0755) 8801-8537

**QQ**: 156368415 智能机器人2019

**Web**: *http://hqlab.sustc.science/teaching/*

# Class Schedule

- **Lectures**: T 8:00 am - 9:50 am Lychee Hills Building 1 Room 102
- **Lab**: T 10:20 am – 12:10 pm Lychee Hills Building 6 Room 406
  Research building 1, $2^{nd}$ Floor
- **Grading policy**

| | | | |
|---|---|---|---|
| Assignment (8~10 times): | 15% | Quiz (5~10 times): | 10% |
| Midterm Exam : | 15% | Final Exam | 15% |
| Projects (2 per group): | 15% | Final Projects: | 30% |

| | | |
|---|---|---|
| 90~93: A- | 94~97: A | 98~100: A+ |
| 80~82: B- | 83~86: B | 87~89: B+ |
| 70~72: C- | 73~76: C | 77~79: C+ |
| 60~62: D- | 63~66: D | 67~69: D+ |

# Textbook and Lecture Notes

**Textbooks**:

[1] Probabilistic Robotics, by Sebastian Thrun, Dieter Fox, and Wolfram Burgard

**Other books:**

[1] Robotics: Control, Sensing, Vision, and Intelligence, by Fu King Sun

[2] Introduction to Autonomous Mobile Robots, by Roland Siegwart

[3] Robot Programming, Cameron Hughes and Kacey Hughes

**Lecture notes**:

http://hqlab.sustc.science/teaching/

# Other Resources

**Assignment platform**: sakai.sustc.edu.cn

**Textbook pdf**: http://www.doc88.com/p-3951558082918.html

# Teaching Objectives

- Fundamental knowledge of many of the basic tasks of intelligent mobile robots: locomotion, estimation, localization, planning, reconstruction and exploration.

- Intelligent robot system development methods with C/C++/Python through labs and projects

- Intelligent robot system design, integration, and verification skills through the final project, literature surveys and reports

# Lecture Schedule

Section 00 Course Introduction
Section 01 Mobile Robots, Control and Decision Architecture
Section 02 Locomotion and Sensors
Section 03 Probabilistic Motion and Sensor Models
Section 04 Motion Planning and Collision Avoidance
Section 05 Occupancy and Mapping
Section 06 Particle and Kalman Filters
===Midterm Exam==
Section 07 Error Propagation and Feature Estimation
Section 08 Localization
Section 09 SLAM
Section 10 Path Planning and Navigation
Section 11 Reconstruction and Exploration
===Final Exam===

# Lab Schedule

Section 00 Lab Tour
Section 01 Simulation Platform
Section 02 Experiment Platform
===Proposal===
Section 03 Robot Perception
Section 04 Robot Control and Decision
Section 05 Robot Communications
Section 06 Motion Planning and Collision Avoidance
Section 07 Occupancy and Mapping
Section 08 Robot Localization
Section 09 SLAM
Section 10 Path Planning and Navigation
===Final Report===

# Filed Trips

- Visit Companies
- Survey Papers
- Bonus Credits

# Plagiarism

**From Spring 2018**, the plagiarism policy applied by the Computer Science and Engineering department is the following:

* If an assignment is found to be plagiarized, the first time the score of the assignment will be 0.

- The second time the score of <u>the course</u> will be 0.

As **it may be difficult** when two assignments are identical or nearly identical who actually wrote it, the policy will apply to BOTH students, unless one confesses having copied without the knowledge of the other.

# What is OK, and what isn't OK

**It's OK**

- to work on an assignment with a friend, and think together about the program structure, share ideas and even the global logic. At the time of actually writing the code, you should write it alone.
- to use in an assignment a piece of code found on the web, as long as you indicate in a comment where it was found and don't claim it as your own work.
- to help friends debug their programs (you'll probably learn a lot yourself by doing so).
- to show your code to friends to explain the logic, as long as the friends write their code on their own later.

**It's NOT OK**

- **to take the code of a friend, make a few cosmetic changes (comments, some variable names) and pass it as your own work.**

# Make a Promise to Keep

**Sign**

the “Student Commitment for Assignments”

**Keep**

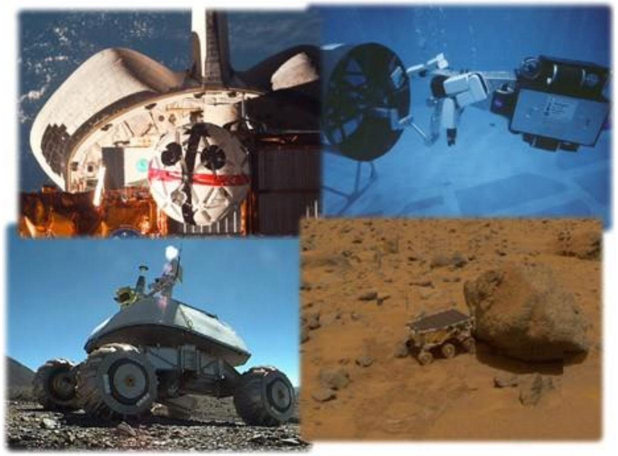
the promise during the whole semester!

# Outlines

- Robot Types and Framework
- Problem Statement
- Related Areas
- History
- Optimization for Intelligent Robots
- Algorithms
- Platforms and Demos

# Robot Types

- Robot Manipulators
  - Assembly, automation
- Field robots
  - Military applications
  - Space exploration
- Service robots
  - Cleaning robots
  - Medical robots
- Entertainment robots



# Robot Manipulators

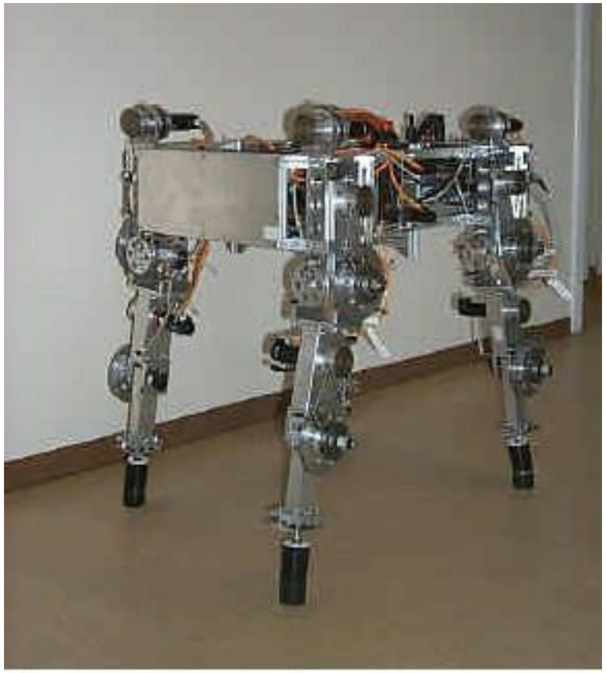
- Static Manipulators

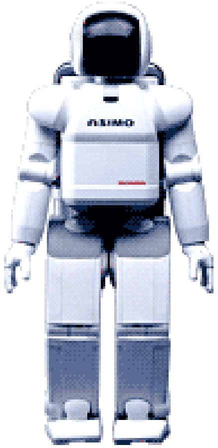
- Mobile Manipulators

# Field Robots: Locomotion

Aerial Robots

Wheeled mobile robots






Humanoid

Underwater robots

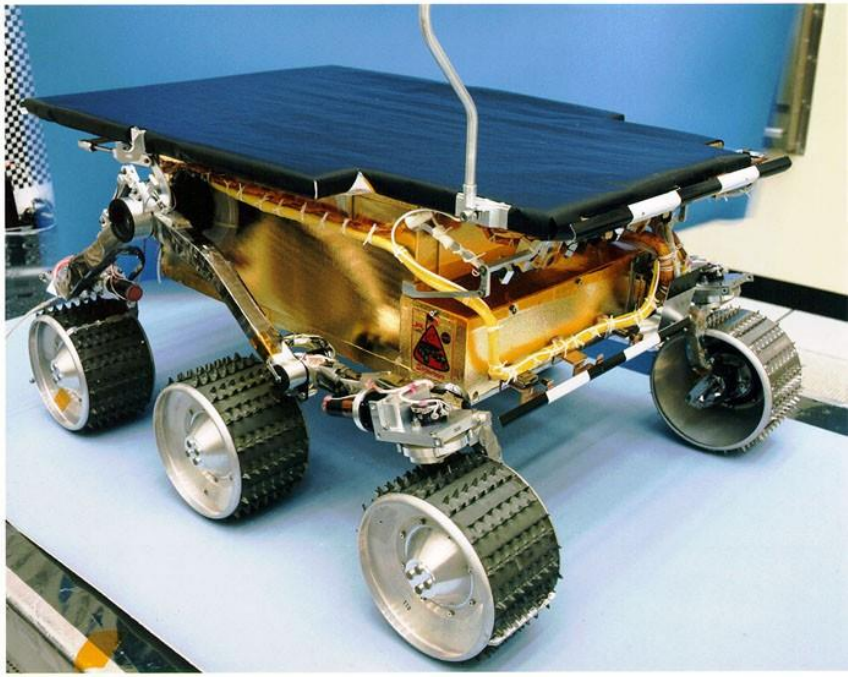
Legged robots

# Field Robots: Mobile

Hilare II

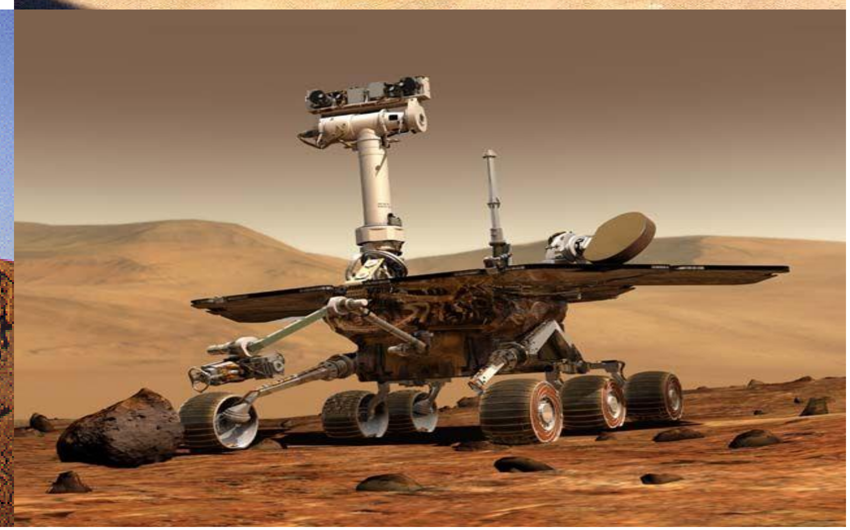

http://www.laas.fr/~matthieu/robots/

Sojourner Rover



NASA and JPL, Mars exploration

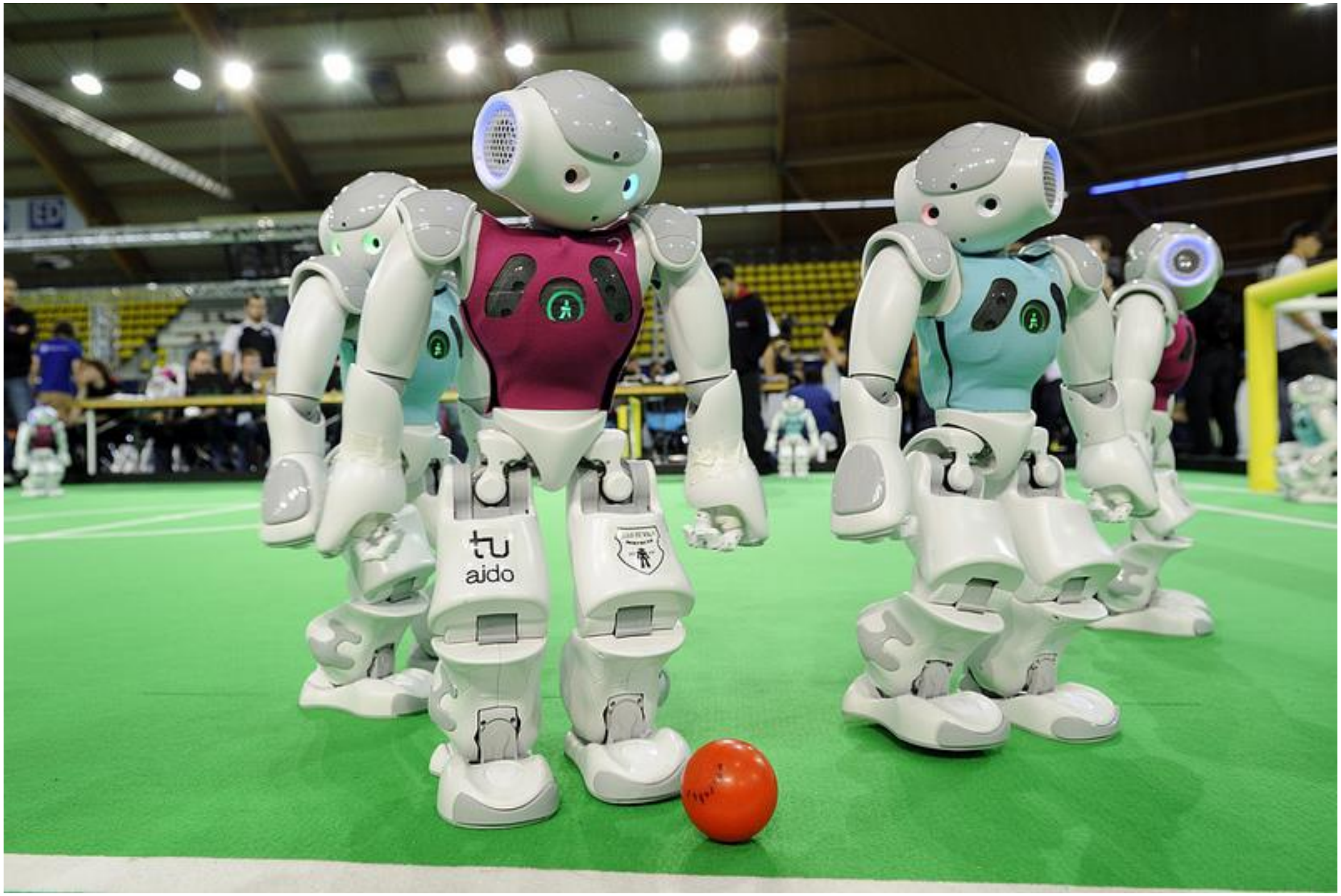
# Field Robots: Autonomous



# Service Robots

iRobot Scooba Robot

# Entertainment Robots

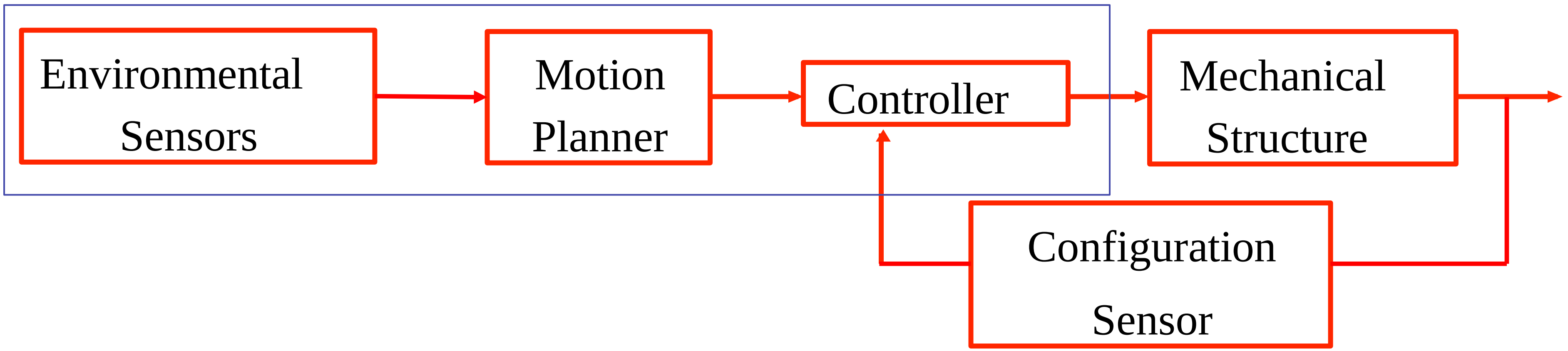


# Why Use Robots?

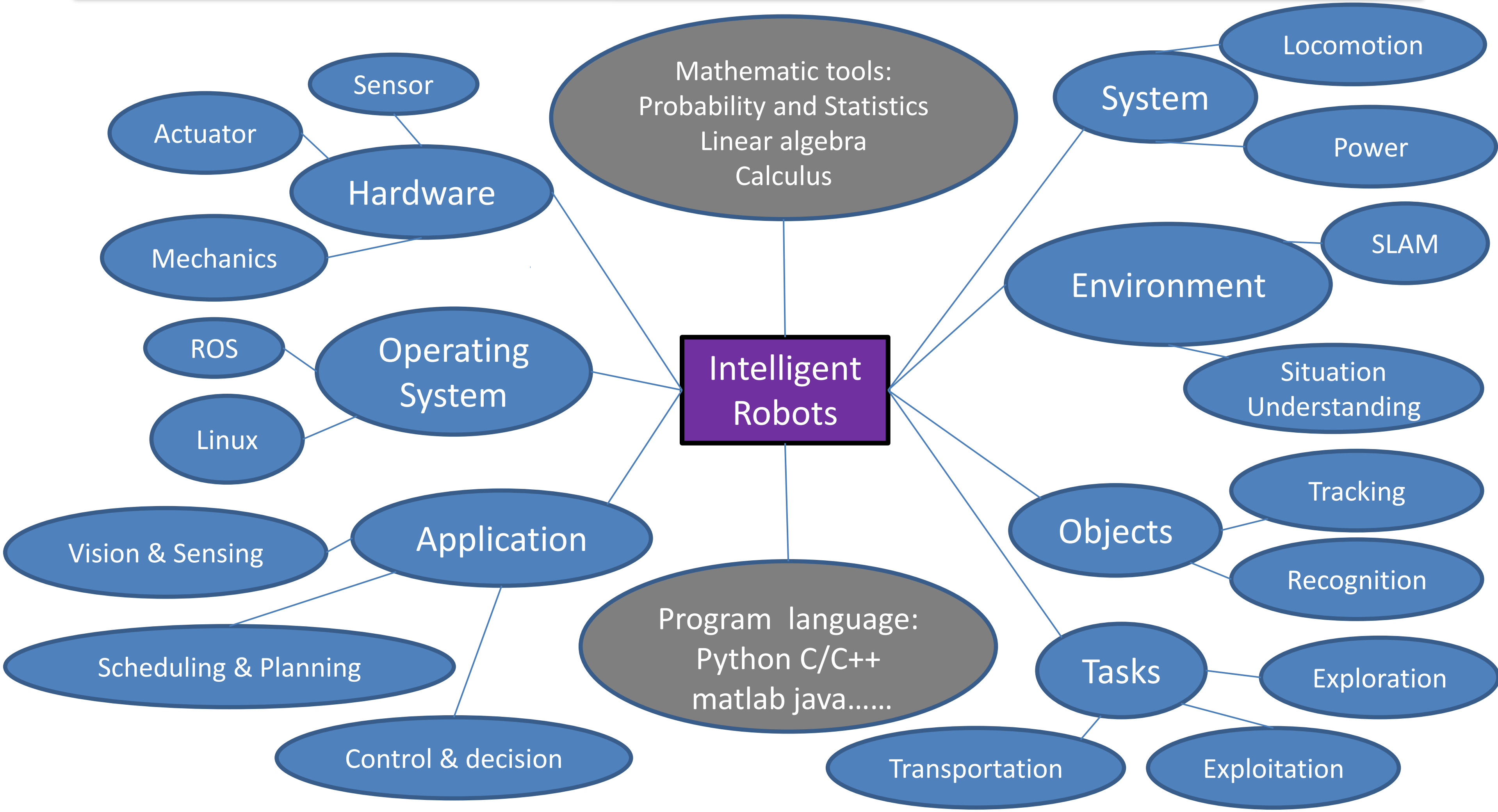
- Application in 4D environments
  - Dangerous
  - Dirty
  - Dull
  - Difficult
- 4A tasks
  - Automation
  - Augmentation
  - Assistance
  - Autonomous

# Architecture of Robotic Systems

- Mechanical Structure
  - Kinematics and dynamics
- Actuators:
  - Electrical, hydraulic, pneumatic, artificial muscle
- Sensors
  - Passive：optical，infrared, electro-magnetic，acoustic，IMU，GPS
  - Active: laser, ultrasound, microwave
- Computation，communication, and control
- User interface and power unit



# Framework



Mathematic tools:
Probability and Statistics
Linear algebra
Calculus
Sensor
Actuator
Hardware
Mechanics
ROS
Operating System
Linux
Vision & Sensing
Application
Scheduling & Planning
Control & decision
Intelligent Robots
Program language:
Python C/C++
matlab java……
Locomotion
System
Power
SLAM
Environment
Situation Understanding
Tracking
Objects
Recognition
Tasks
Exploration
Transportation
Exploitation

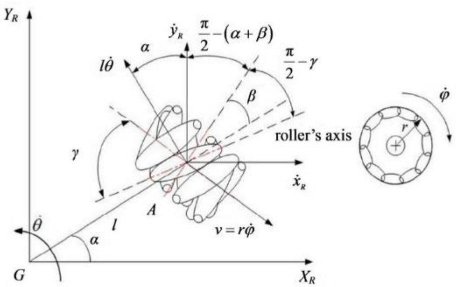
# Outlines

- Robot Types and Framework
- Problem Statement
- Related Areas
- History
- Optimization for Robots
- Algorithms
- Platforms and Demos

# Problem Statement

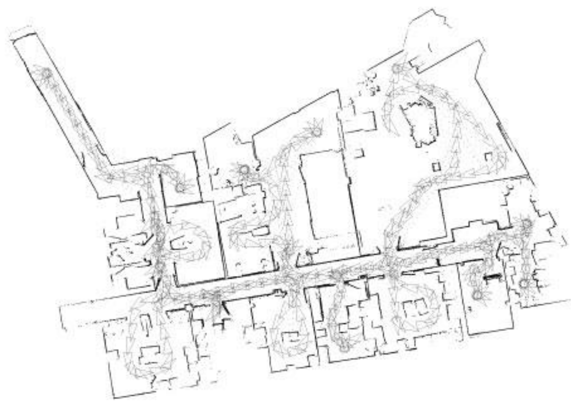
- **Problems:**

  - **Motion Control**




$$\begin{bmatrix}\dot{x}_I\\ \dot{y}_I\\ \dot{\theta}\end{bmatrix} = -\left(\sqrt{2}/2\right) r\boldsymbol{J}^{+}\begin{bmatrix}\dot{\varphi}_1\\ \dot{\varphi}_2\\ \dot{\varphi}_3\\ \dot{\varphi}_4\end{bmatrix}$$

  - **Range Sensing**
  - **Mapping**
  - **Stereo Vision**
  - **Reconstruction**

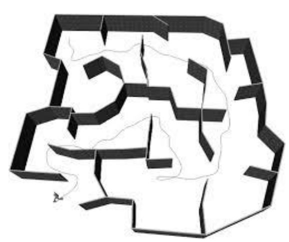


$$\underbrace{\begin{pmatrix}P_x(k+1)\\ P_y(k+1)\\ V_x(k+1)\\ V_y(k+1)\end{pmatrix}}_{X(k+1)} = \underbrace{\begin{pmatrix}1&0&T&0\\0&1&0&T\\0&0&1&0\\0&0&0&1\end{pmatrix}}_{A}\underbrace{\begin{pmatrix}P_x(k)\\ P_y(k)\\ V_x(k)\\ V_y(k)\end{pmatrix}}_{X(k)} + \underbrace{\begin{pmatrix}0\\0\\ \sigma_v\\ \sigma_v\end{pmatrix}}_{w(k)}$$

  - **Tracking**
  - **Recognition**
  - **SLAM**

$$\underbrace{\begin{pmatrix}P_x(k)\\ P_y(k)\end{pmatrix}}_{Y(k)} = \underbrace{\begin{pmatrix}1&0&0&0\\0&1&0&0\end{pmatrix}}_{C}\underbrace{\begin{pmatrix}P_x(k)\\ P_y(k)\\ V_x(k)\\ V_y(k)\end{pmatrix}}_{X(k)} + \underbrace{\begin{pmatrix}\sigma_p\\ \sigma_p\end{pmatrix}}_{v(k)}$$

  - **Motion Planning**
  - **Path Planning**

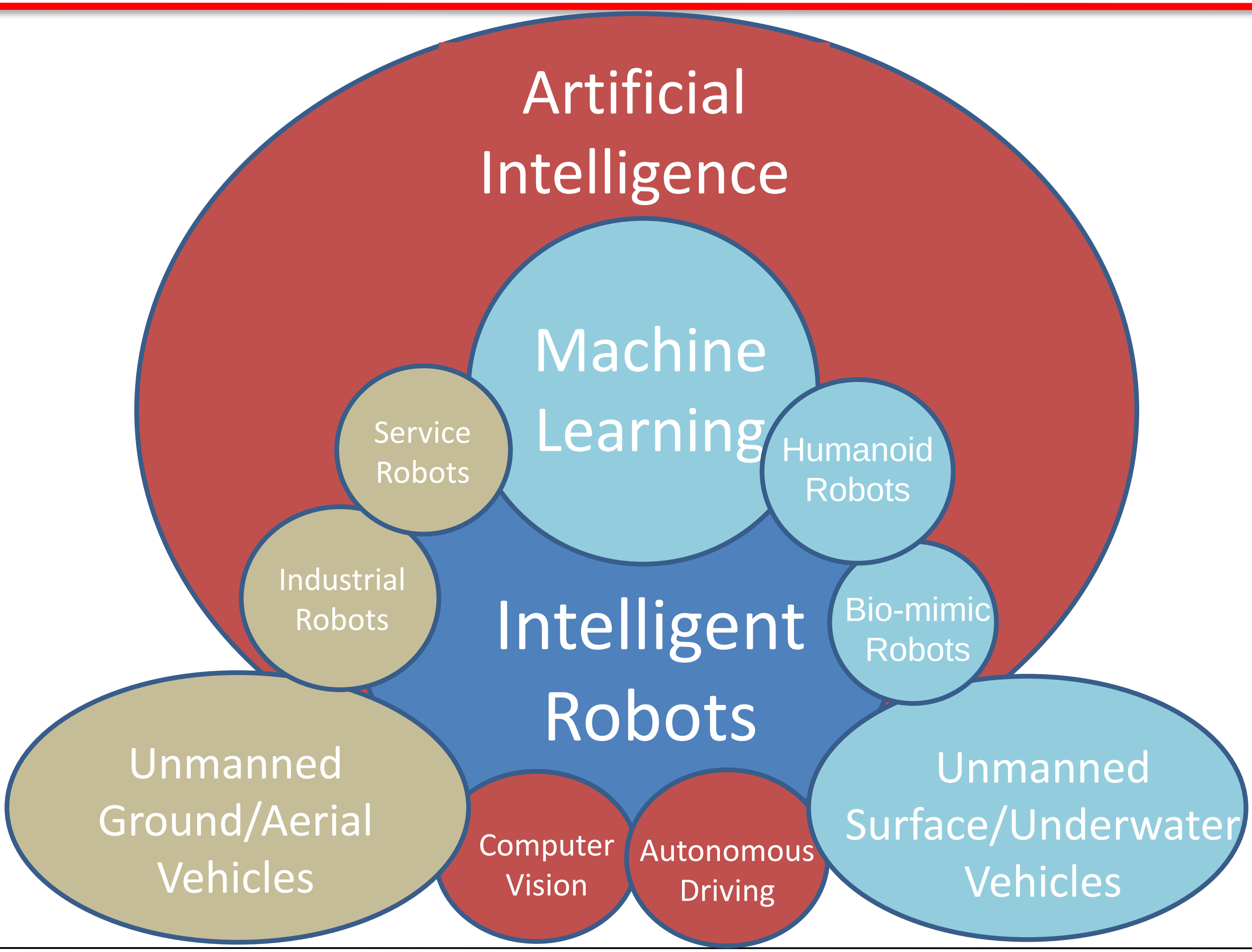


$$f(n) = g(n) + h(n)$$

# Outlines

- Robot Types and Framework
- Problem Statement
- Related Areas
- History
- Optimization for Intelligent Robots
- Algorithms
- Platforms and Demos

# Related Areas



# What is AI

- Knowledge representation
- Understanding natural language
- Learning
- Planning and problem solving
- Inference
- Search
- Vision

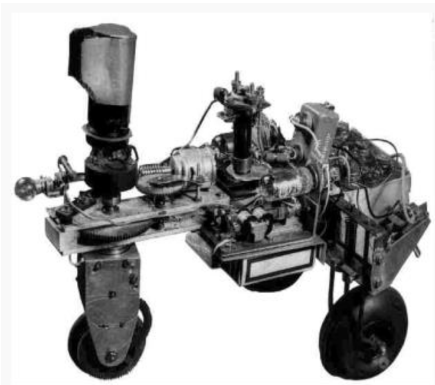
# Learning and Evolution

- Learning
  - Skills vs Task (Map acquisition)
- Learning Methods
  - Learning by instruction
  - Learning by imitation
  - Learning by skill transfer
  - Learning by trial-and-error
- Evolution and adaptation

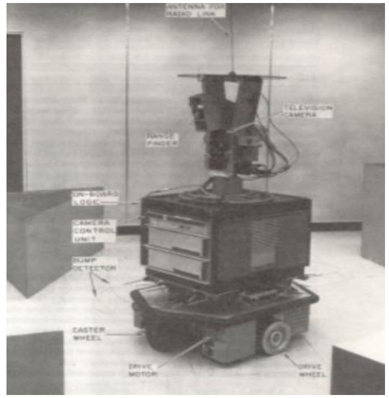
# Outlines

- Robot Types and Framework
- Problem Statement
- Related Areas
- History
- Optimization for Intelligent Robots
- Algorithms
- Platforms and Demos

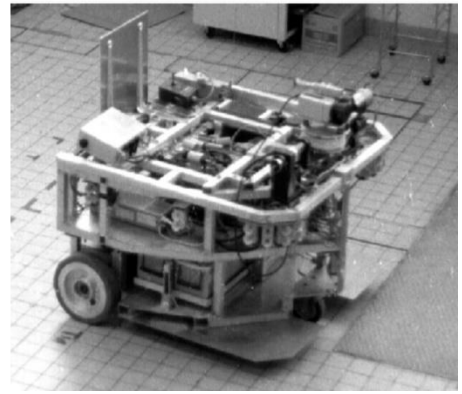
# History



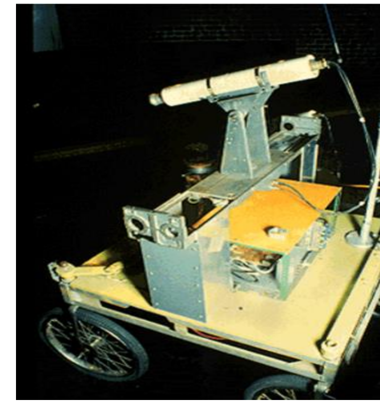
1950 Grey Walter



1969 Shakey



1977 Hilare 1



1979 Stanford Car

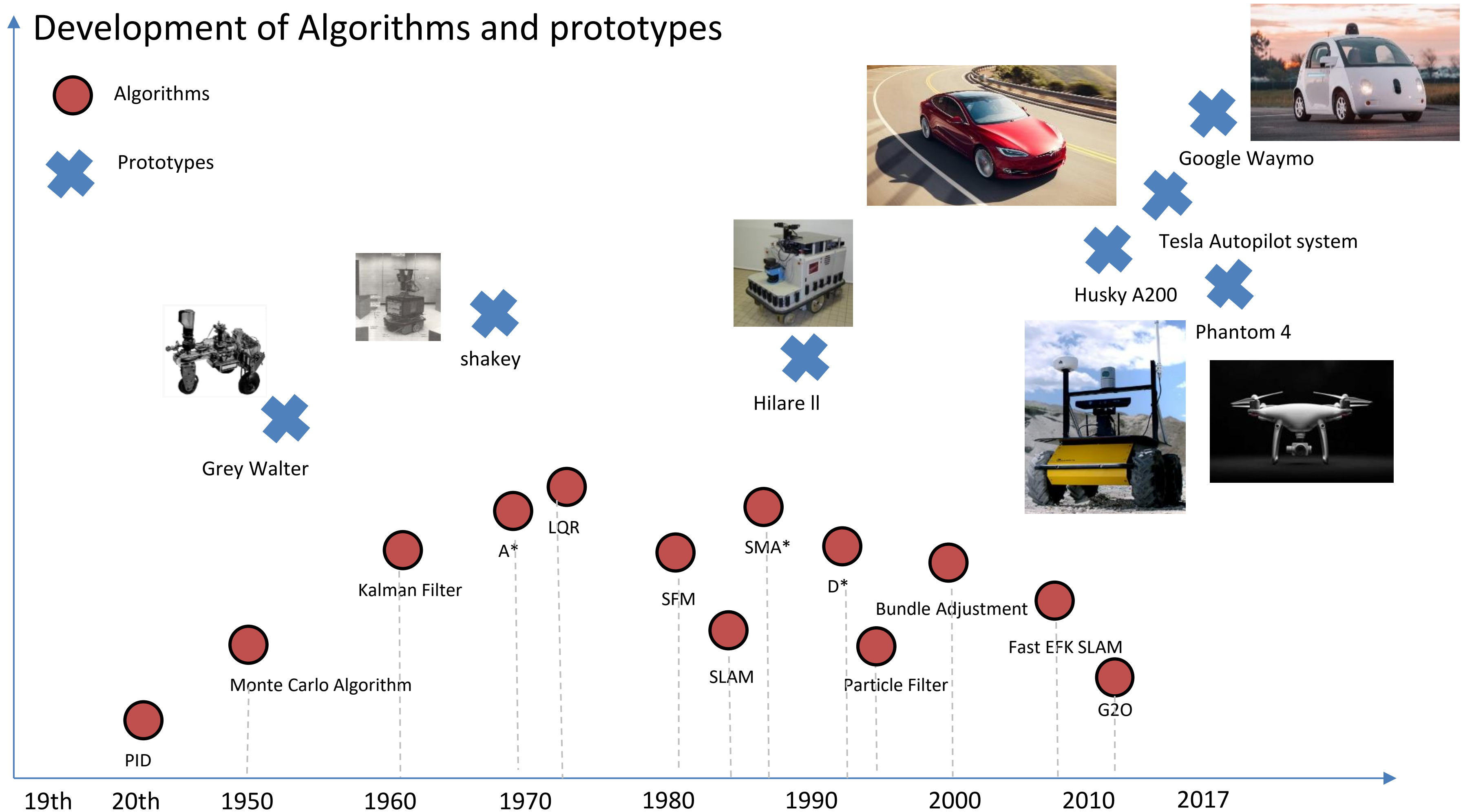
1990 Hilare ll


1998-2000 RAMS

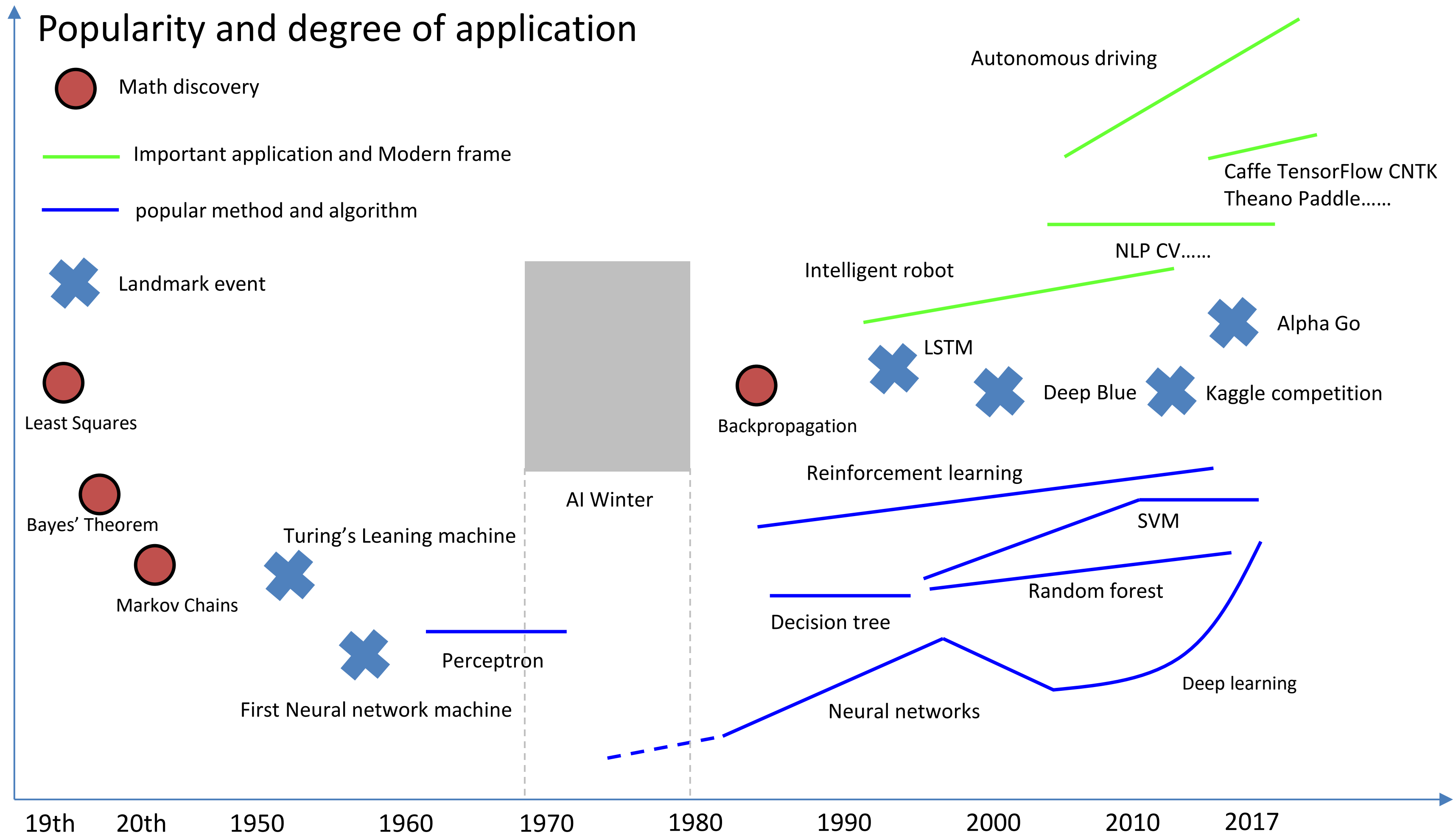
2011 husky a200

2017 Waymo

# History


Development of Algorithms and prototypes
Algorithms
Prototypes
Grey Walter
shakey
Hilare II
Google Waymo
Tesla Autopilot system
Husky A200
Phantom 4
PID
Monte Carlo Algorithm
Kalman Filter
A*
LQR
SFM
SLAM
SMA*
D*
Particle Filter
Bundle Adjustment
Fast EFK SLAM
G2O
19th
20th
1950
1960
1970
1980
1990
2000
2010
2017

# History



Popularity and degree of application
Math discovery
Important application and Modern frame
popular method and algorithm
Landmark event
Least Squares
Bayes' Theorem
Markov Chains
Turing's Leaning machine
First Neural network machine
Perceptron
AI Winter
Backpropagation
LSTM
Deep Blue
Kaggle competition
Alpha Go
Intelligent robot
NLP CV……
Caffe TensorFlow CNTK
Theano Paddle……
Autonomous driving
Reinforcement learning
SVM
Random forest
Decision tree
Neural networks
Deep learning
19th
20th
1950
1960
1970
1980
1990
2000
2010
2017

# Outlines

- Robot Types and Framework
- Problem Statement
- Related Areas
- History
- Optimization for Intelligent Robot
- Algorithms
- Platforms and Demos

# Optimization for Intelligent Robots

- **Perception**
  - Estimation / Prediction / Classification
  - Fusion / Mapping / Reconstruction
  - Situation understanding
- **Control**
  - Kinematics / Dynamics Control
  - Optimal/Robust control
  - Adaptive control
- **Decision**
  - Markov Decision Process
  - Information Gain Based Exploration
- **Planning**
  - Multi-objectives
  - Path/Motion planning
- **Scheduling**
  - Multi-tasks
  - Resource allocation

# What is optimization?

- Finding (one or more) minimizer of a function subject to constraints

$$\arg\min_{x} \ f_0(x)$$

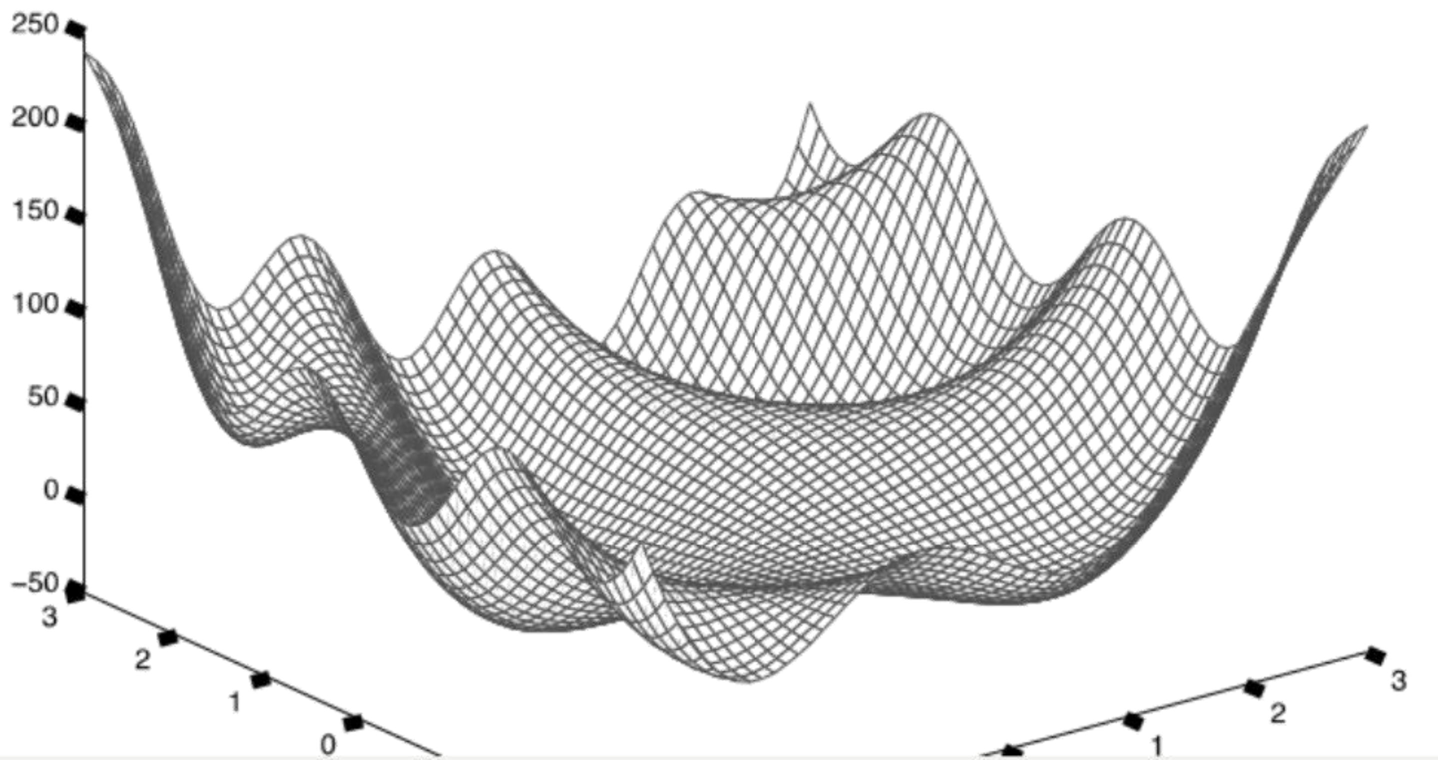
$$s.t. f_i(x) \leq 0, i = \{1, \ldots, k\}$$

$$f_j(x) = 0, i = \{1, \ldots, l\}$$

- Most of the machine learning problems are, in the end, optimization problems

# General Problem

- Minimize f(x)



# Optimization

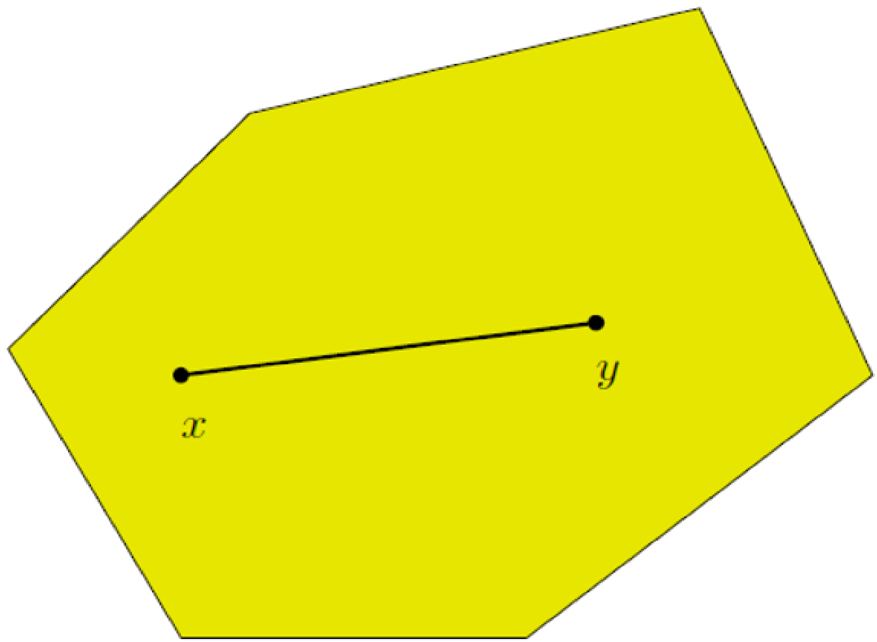
- Convex
  - Unconstrained optimization
  - Constrained optimization
- Non-convex
  - Heuristic algorithms
  - Approximate methods

# What is Convex?

- Convex sets

Def: A set C ⊆ R is convex if for x,y ∈ C; a ∈ [0,1]

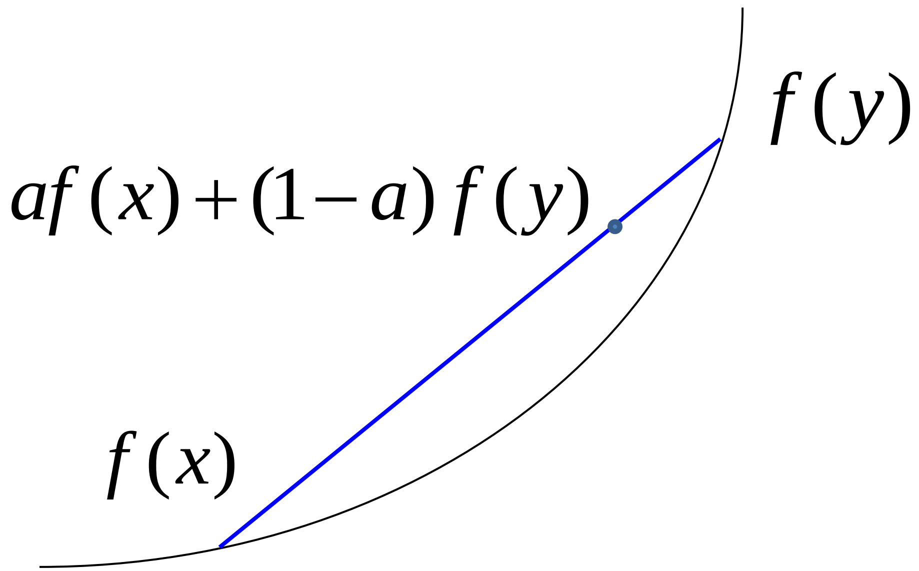
$$ax + (1-a)y \in C$$



# What is Convex?

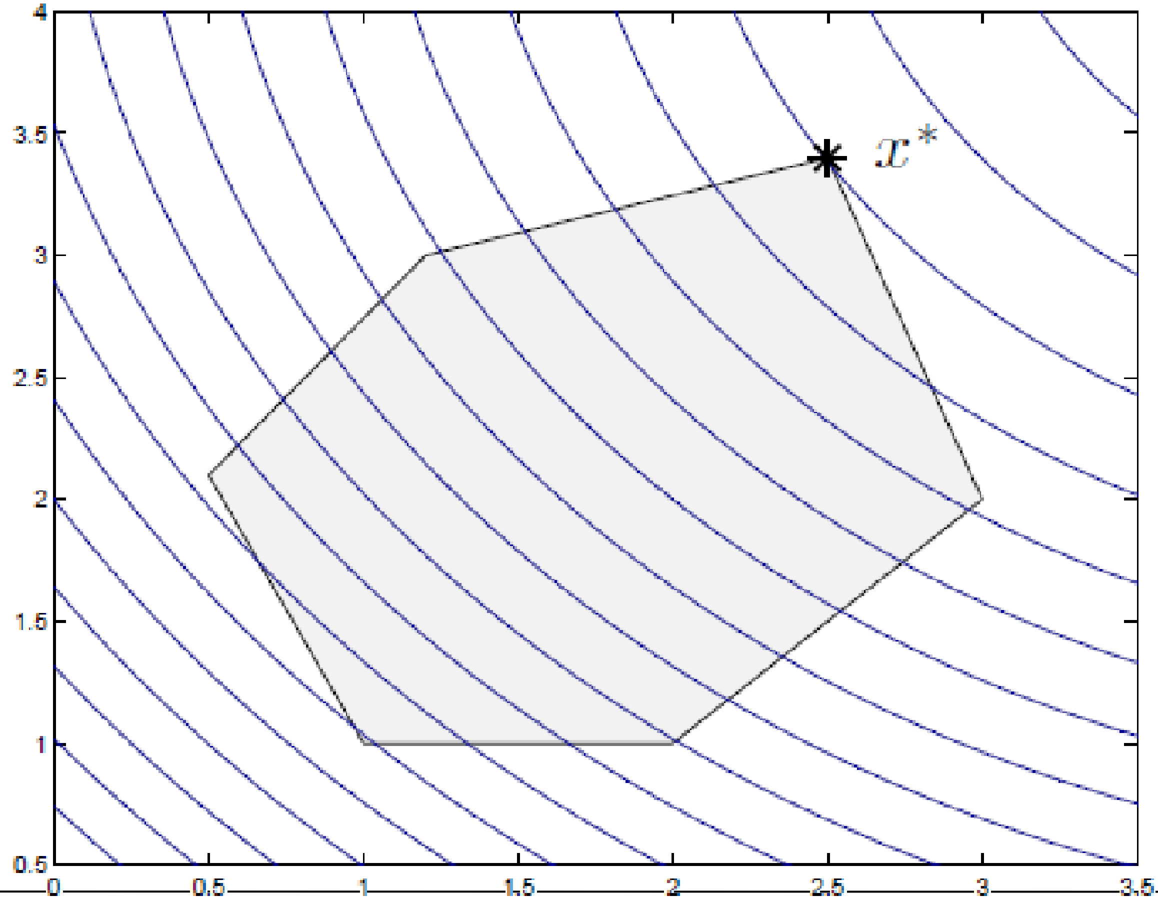
- Convex functions

$$f(ax+(1-a)y) \le af(x)+(1-a)f(y)$$



# Convex Optimization

- Local minimizer = Global minimizer



# Convex Optimization

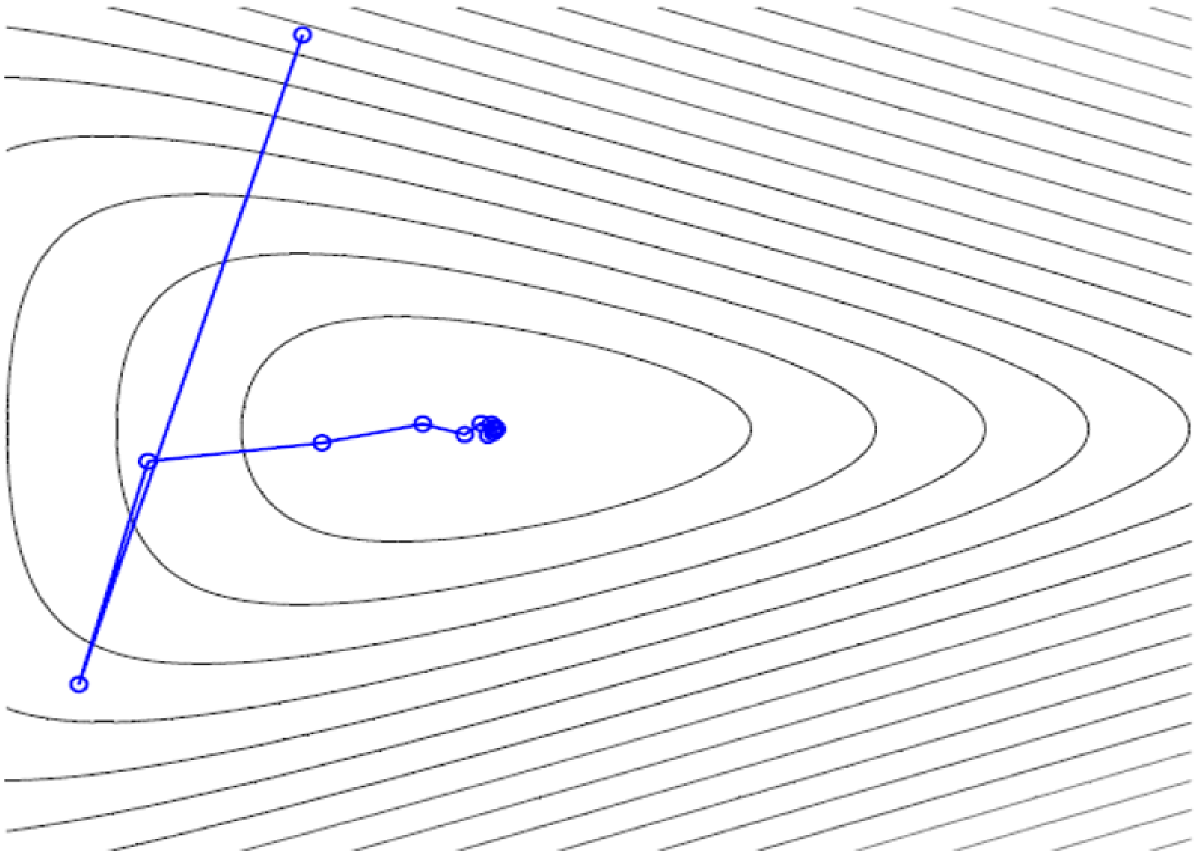
- Unconstrained optimization
  - Gradient descent
  - Newton's method
- Constrained optimization
  - Lagrange function
  - General methods

# Convex optimization

- Unconstrained optimization
  - Gradient descent
  - Newton's method
  - Batch learning
  - Stochastic Gradient Descent
- Constrained optimization
  - Lagrange function
  - General methods

# Gradient Descent

$$f(x_{t+1}) = f(x_t) - \eta \nabla f(x_t)^T (x - x_t)$$



# Newton's Method

- Idea: use a second-order approximation to function

$$f(x+\Delta x) \approx f(x) + \nabla f(x)^T \Delta x + \frac{1}{2}\Delta x^T \nabla^2 f(x) \Delta x$$

- Choose Δx to minimize above:

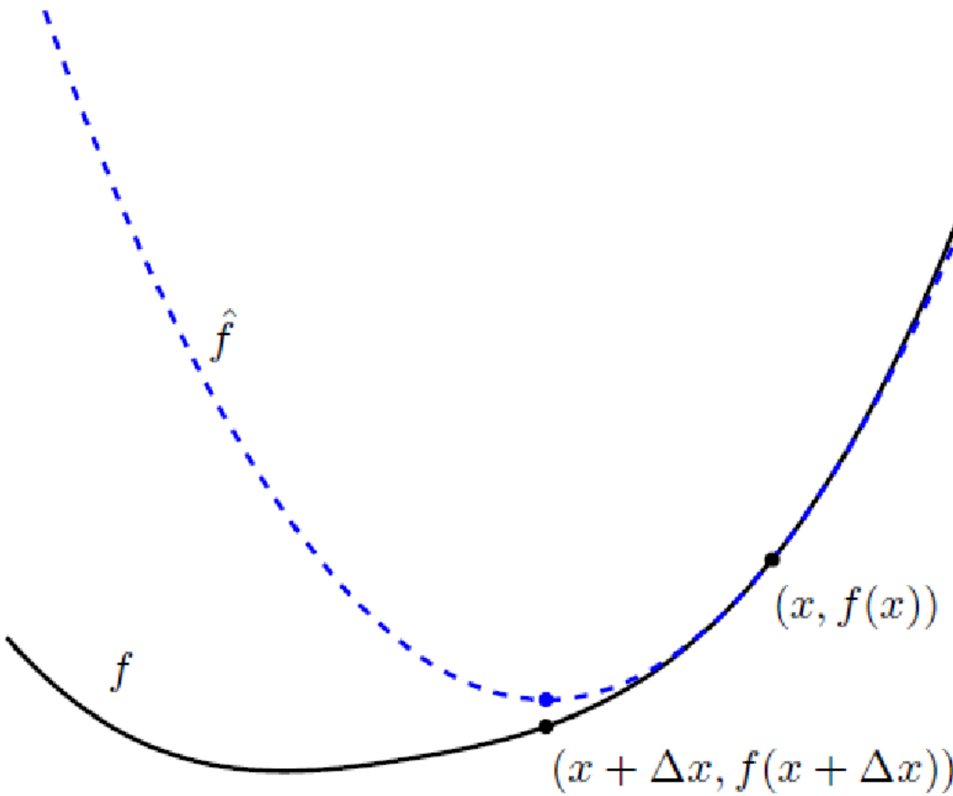
$$\Delta x = -[\nabla^2 f(x)]^{-1} \nabla f(x)$$

- This is descent direction:

$$\nabla f(x)^T \Delta x = -\nabla f(x)^T [\nabla^2 f(x)]^{-1} \nabla f(x) < 0$$

# Newton's Method

$\hat{f}$ is 2-order approximation, $f$ is true function.



# Convex Optimization

- Unconstrained optimization
  - Gradient descent
  - Newton’s method
  - Batch learning
  - Stochastic Gradient Descent
- Constrained optimization
  - Lagrange function
  - General methods

# Lagrange Function

- Start with optimization problem:

$$\arg\min_{x} \; f_0(x)$$

$$s.t. f_i(x) \leq 0, i = \{1, \ldots, k\}$$

$$f_j(x) = 0, i = \{1, \ldots, l\}$$

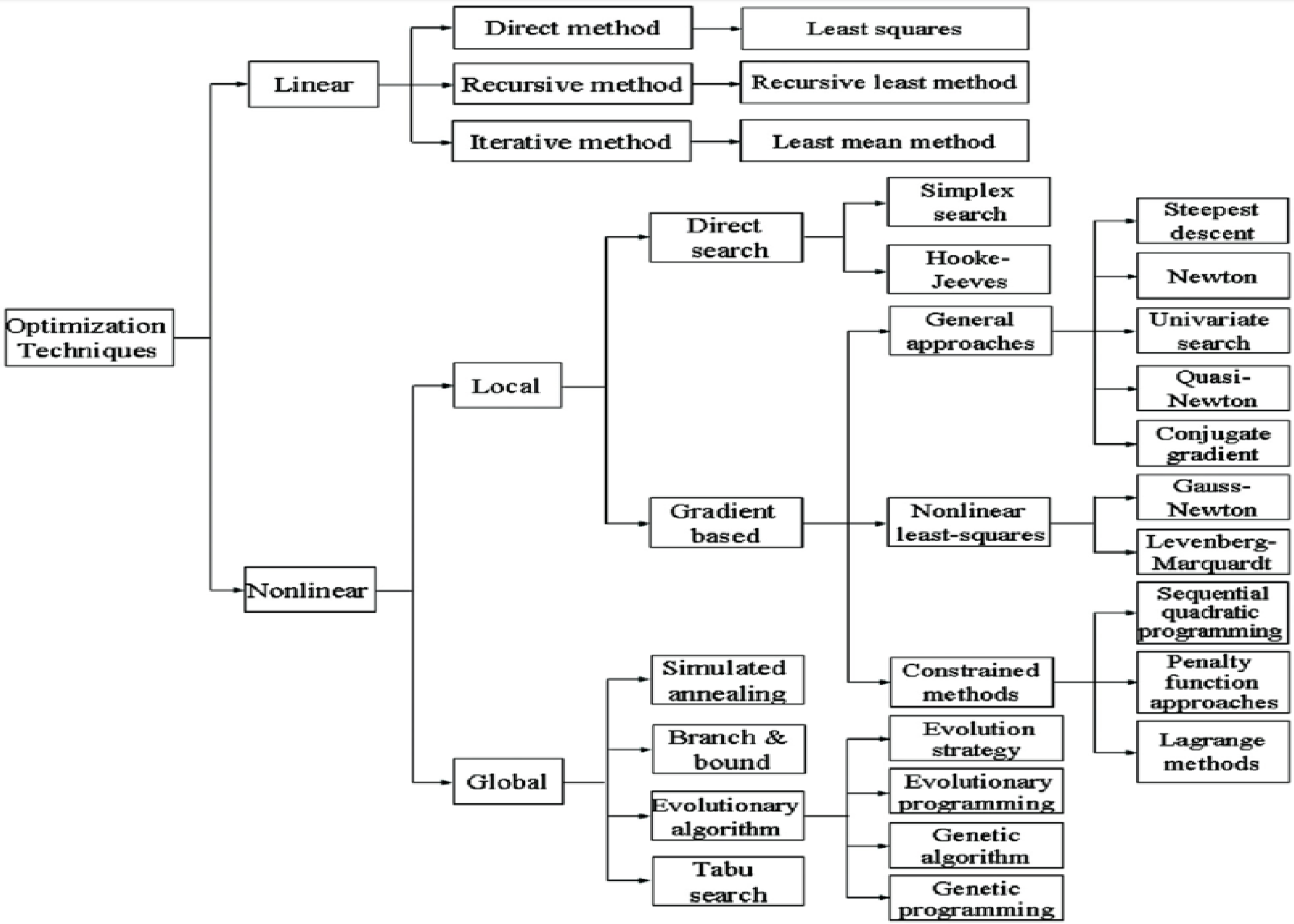
- Is equivalent to min-max optimization:

$$\arg\min_{x} [\sup_{\lambda > 0, \nu} ( f_0(x) + \sum_{i=1}^{k} \lambda_i f_i(x) + \sum_{j=1}^{l} \nu_j h_j(x))]$$

# Optimization

- Convex
  - Unconstrained optimization
  - Constrained optimization
- Non-convex
  - Heuristic algorithms
  - Approximate methods

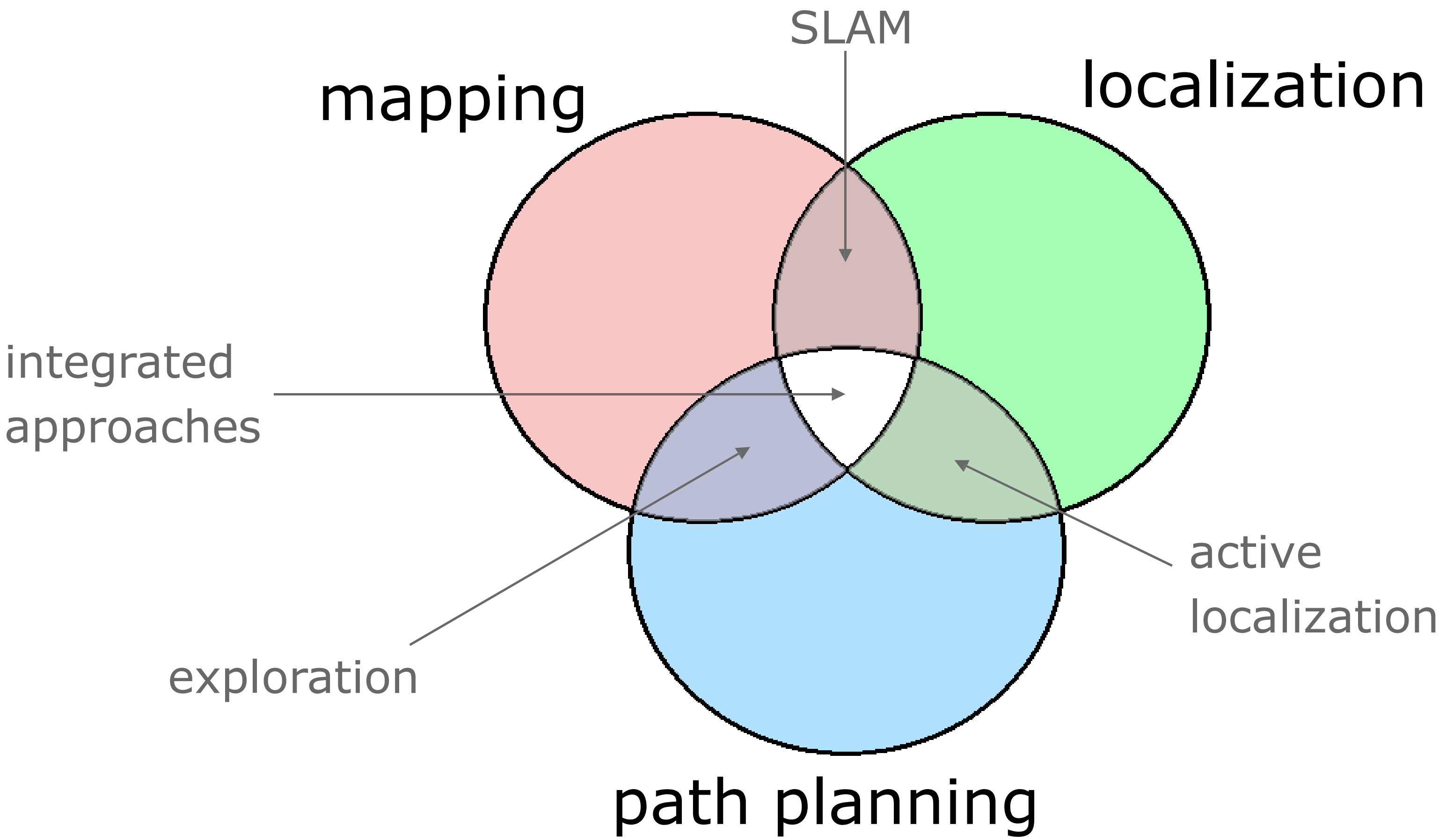
# Optimization Methods



# Outlines

- Robot Types and Framework
- Problem Statement
- Related Areas
- History
- Optimization for Intelligent Robots
- Algorithms
- Platforms and Demos

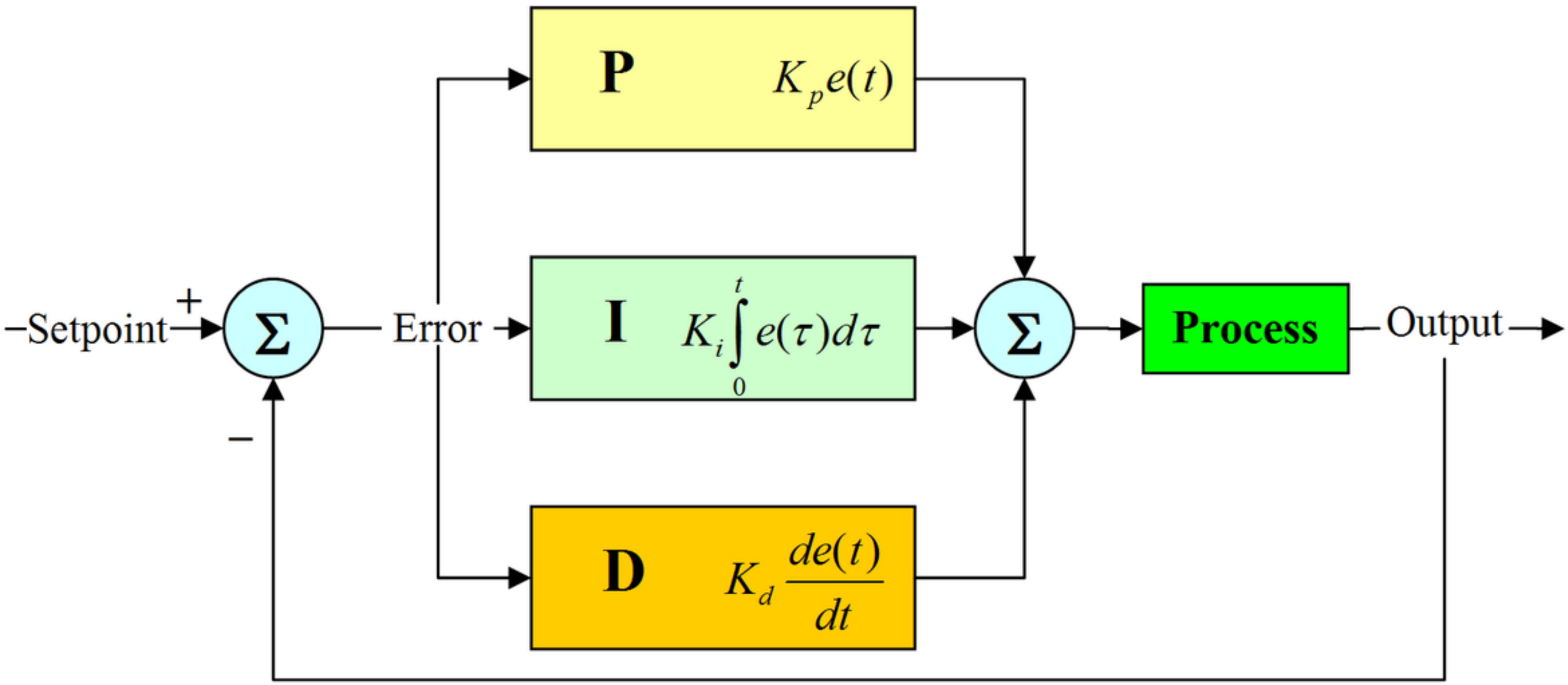
# Tasks of Mobile Robots



# Algorithms

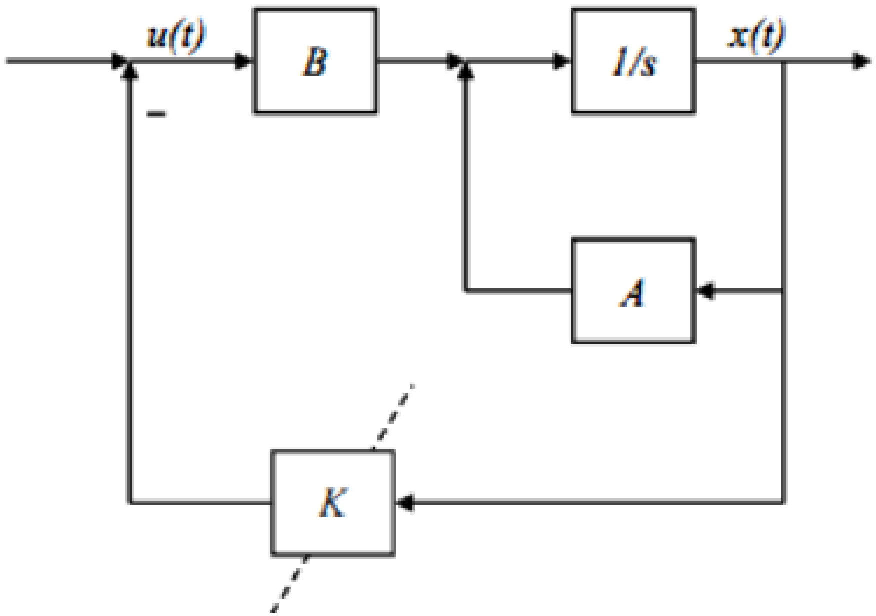
| | |
|---|---|
| Control & Perception | ■ PID, LQR, Sliding Mode<br>■ Kalman Filter<br>■ Structure from motion |
| Motion and Path Planning | ■ A*<br>■ SMA*<br>■ D* |
| Localization & Mapping | ■ Recursive Bayesian estimation<br>■ Gaussian Particle Filter, Monte Carlo localization<br>■ Bundle Adjustment, graph optimization |
| Reconstruction & Exploration | ■ ICP<br>■ igExplore |

# PID



Setpoint
+
−
Σ
Error
P
$K_p e(t)$
I
$K_i \int_0^t e(\tau)d\tau$
D
$K_d \frac{de(t)}{dt}$
Σ
Process
Output

# LQR



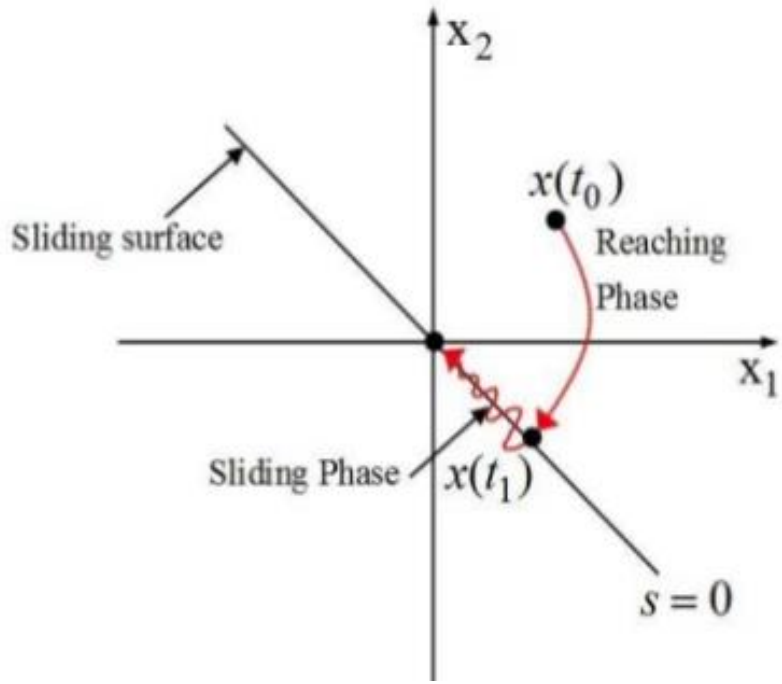

RL in Machine Learning

State space function: $\begin{cases} \dot{x} = Ax + Bu \\ y = Cx + Du \end{cases}$

$u = -Kx$

Optimize function: $J = \frac{1}{2}\int_0^\infty x^T Q x + u^T R u \, dt$

# Sliding Mode



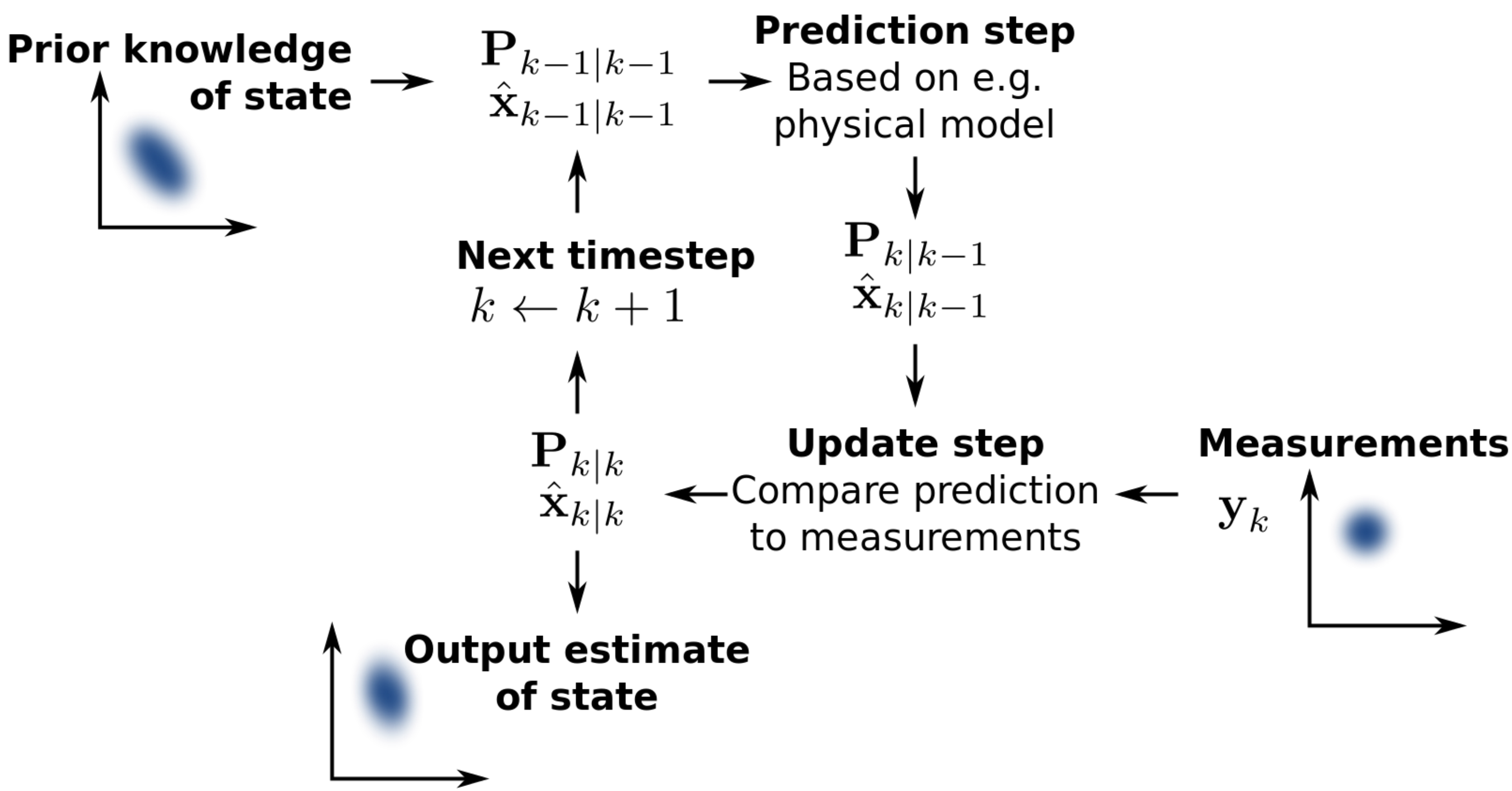

System state equation: $\dot{x} = f(x, u, t)$

Determine switching function: $S(x), S \in R$

Control law:

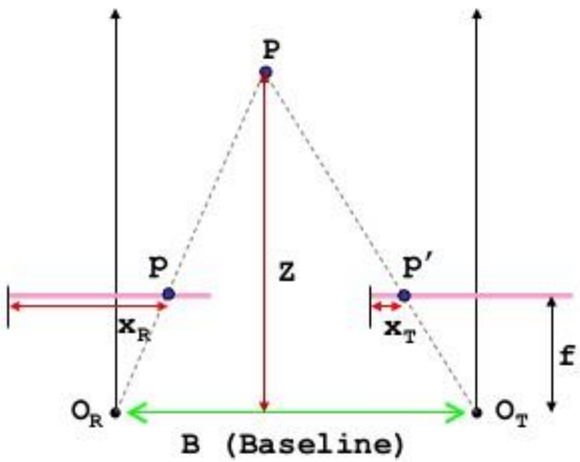
$$u = \begin{cases} u^+(x), S(x) > 0 \\ u^-(x), S(x) < 0 \end{cases}$$

# Kalman Filter



# Stereo Vision

## Disparity and depth



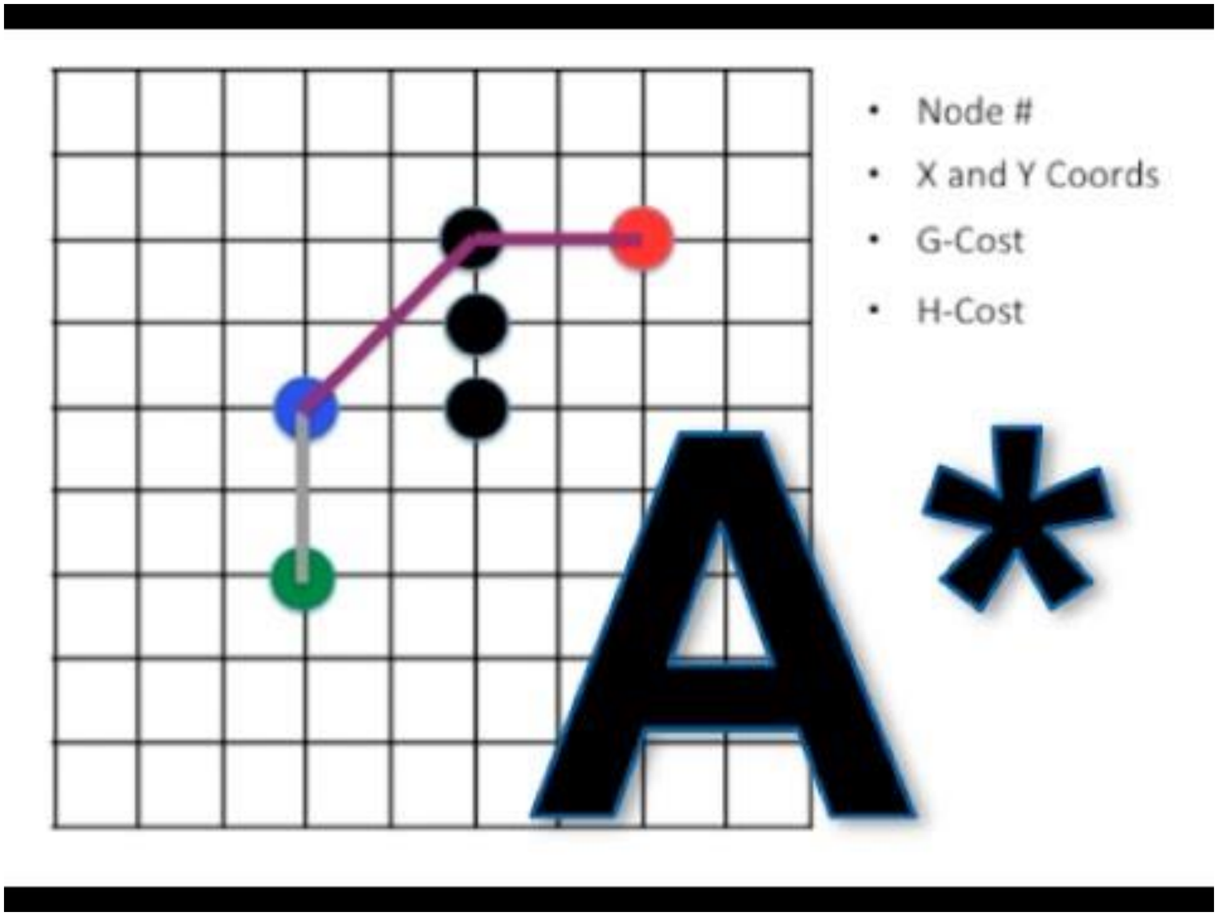

With the stereo rig in standard form and by considering similar triangles ($PO_RO_T$ and $Ppp'$):

$$\frac{b}{Z} = \frac{(b + x_T) - x_R}{Z - f} \;\Rightarrow\; Z = \frac{b \cdot f}{x_R - x_T} = \frac{b \cdot f}{d}$$

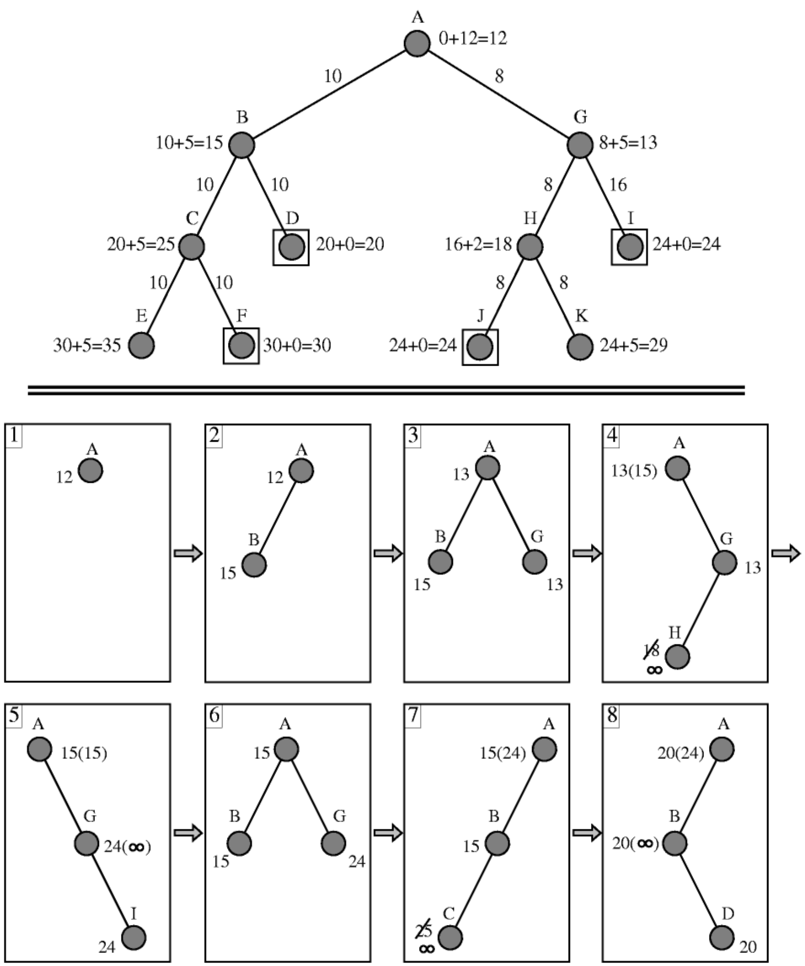
$x_R - x_T$ is the **disparity**

Stefano Mattoccia

# A*



# SMA*


A 0+12=12
10
8
B 10+5=15
G 8+5=13
10
10
8
16
C 20+5=25
D 20+0=20
H 16+2=18
I 24+0=24
10
10
8
8
E 30+5=35
F 30+0=30
J 24+0=24
K 24+5=29
1
A 12
2
A 12
B 15
3
A 13
B 15
G 13
4
A 13(15)
G 13
H 18 ∞
5
A 15(15)
G 24(∞)
I 24
6
A 15
B 15
G 24
7
A 15(24)
B 15
C 25 ∞
8
A 20(24)
B 20(∞)
D 20

# D* Lite

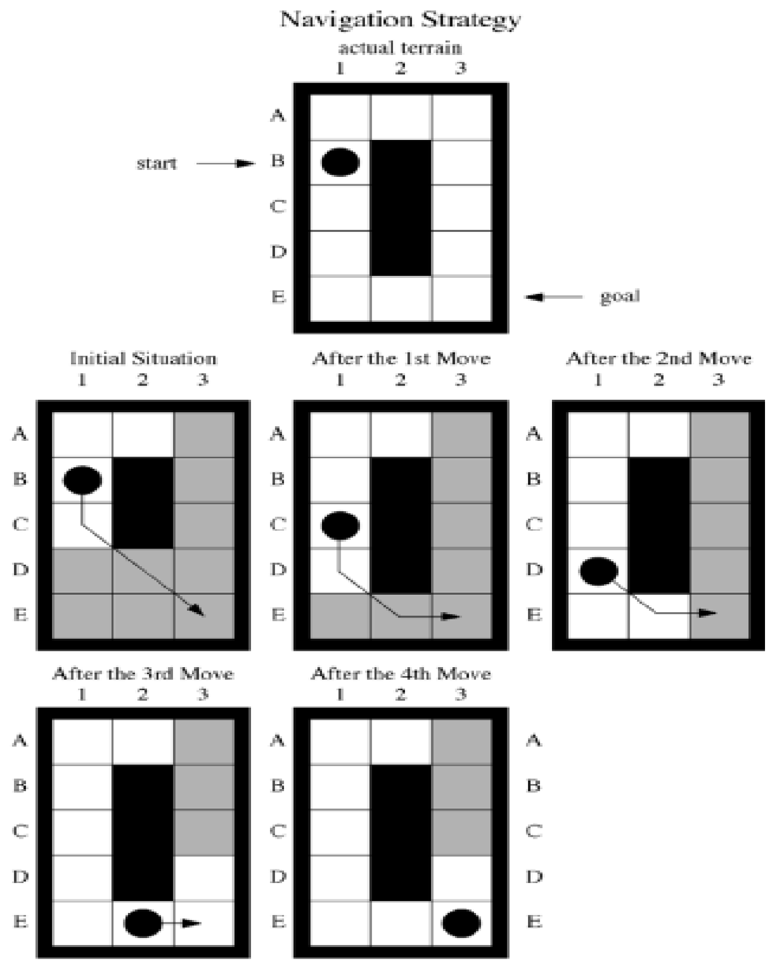
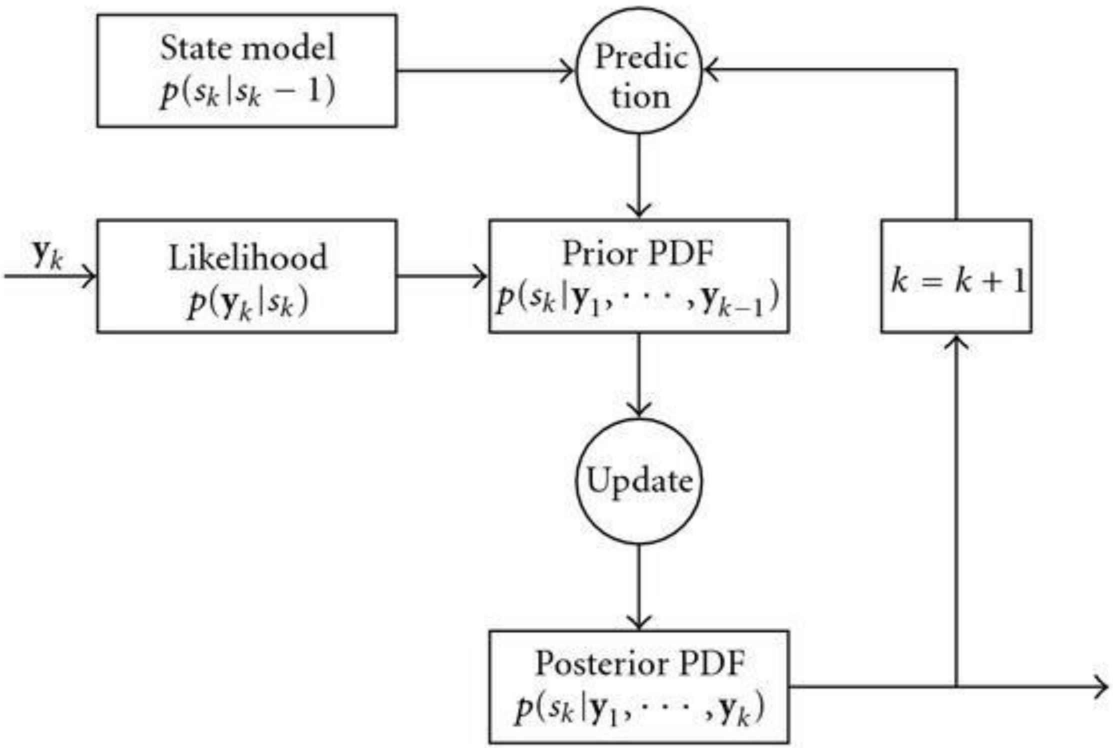
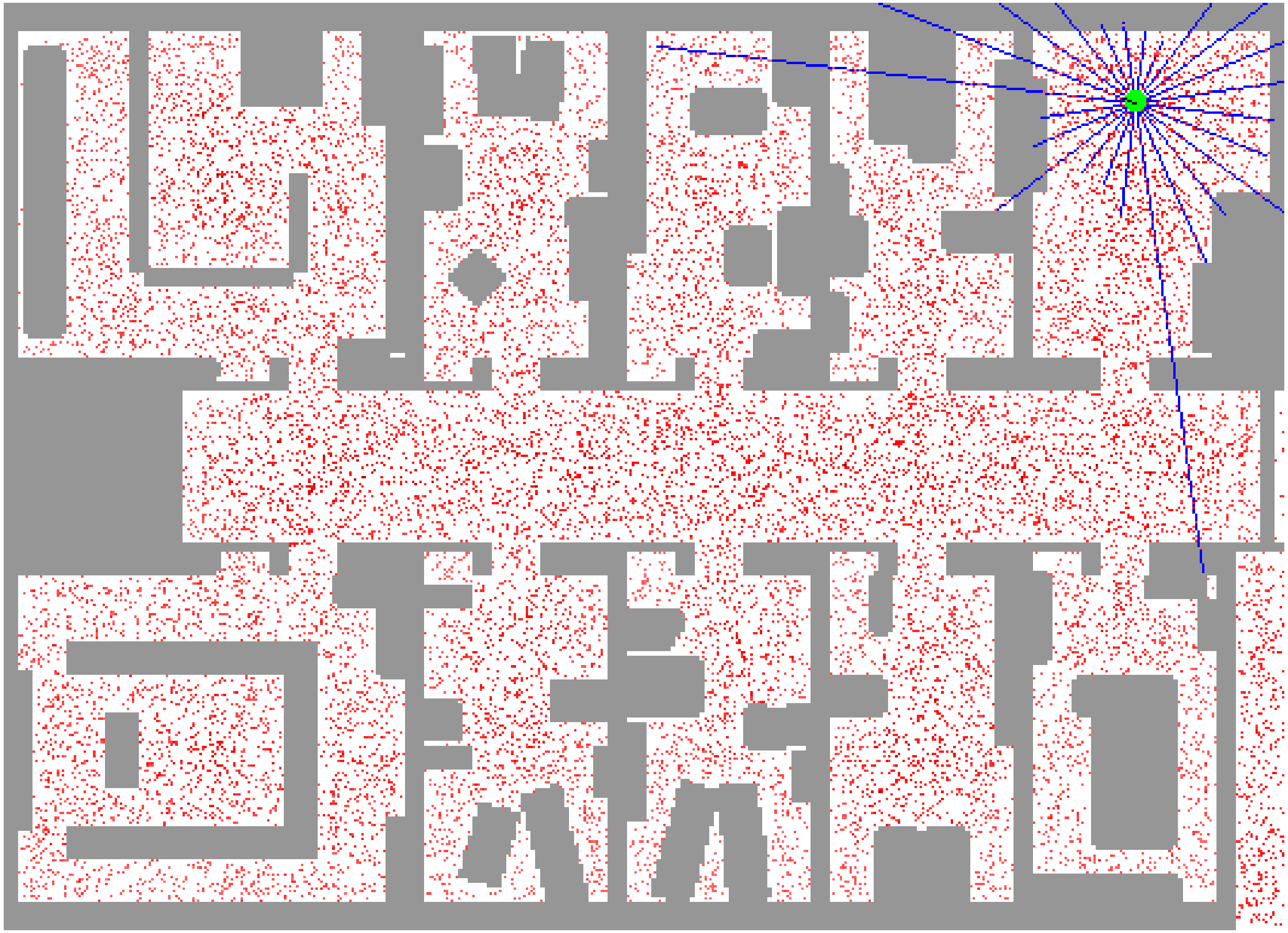



Fig. 1. Illustration of the navigation strategy. Gray cells are cells with unknown blockage status.

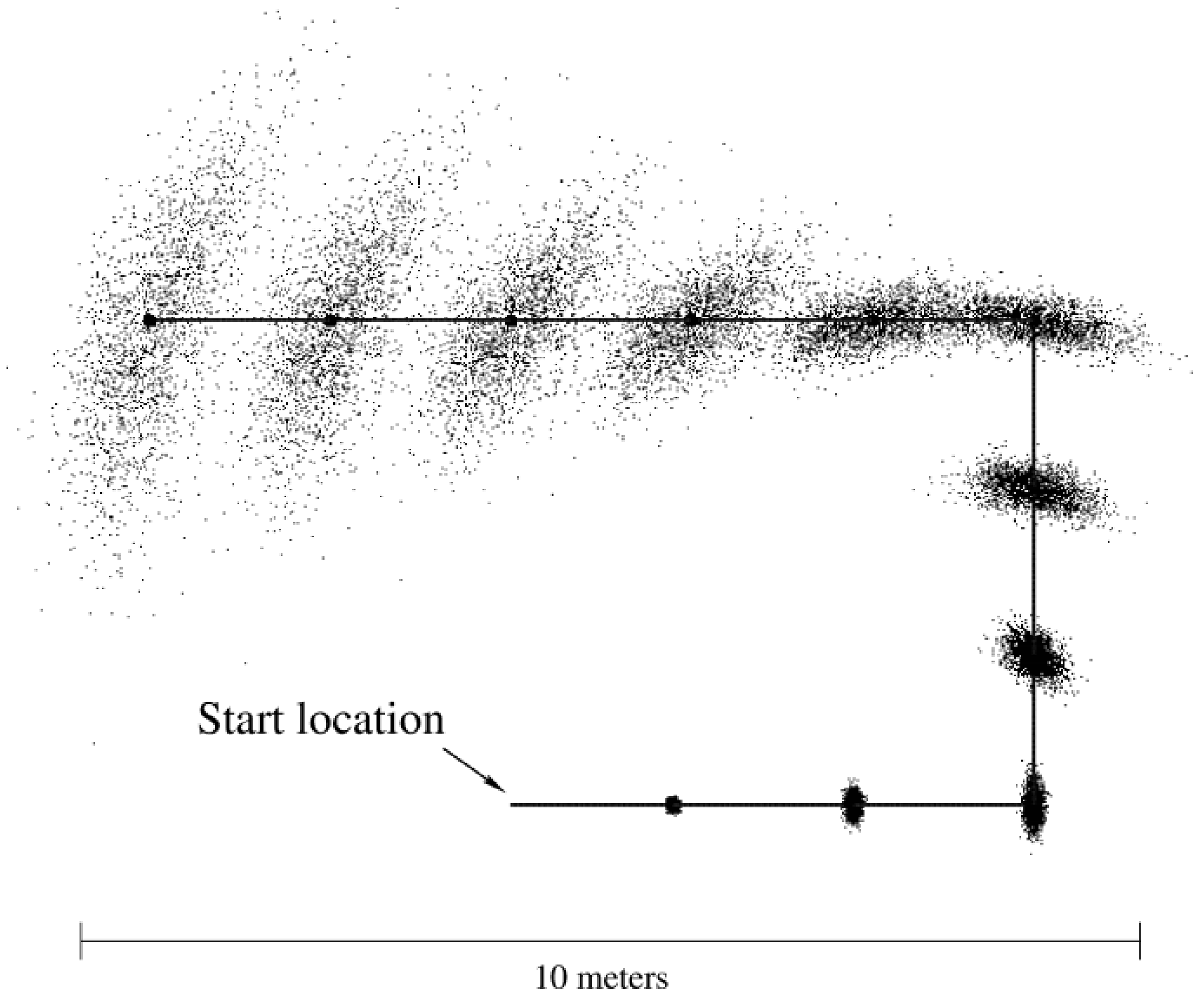
# Recursive Bayesian estimation



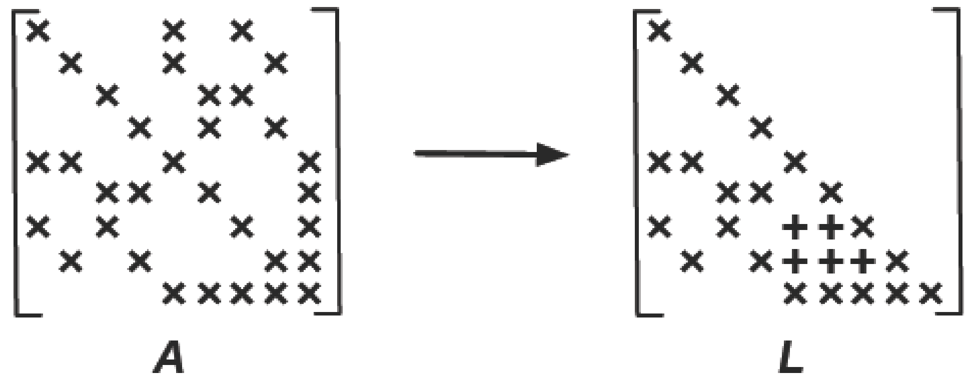
# Gaussian Particle Filter

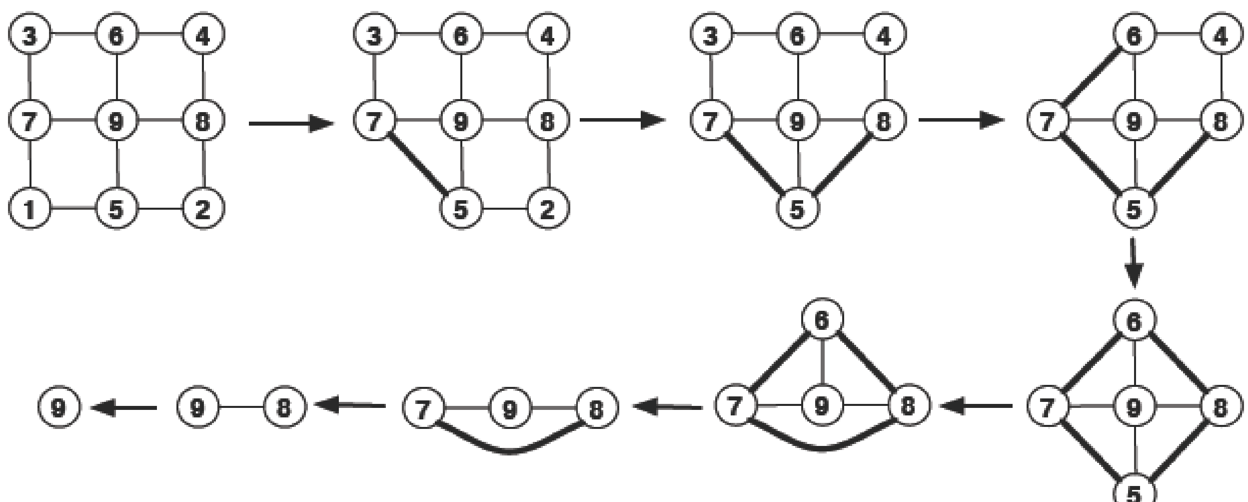


# Monte Carlo localization

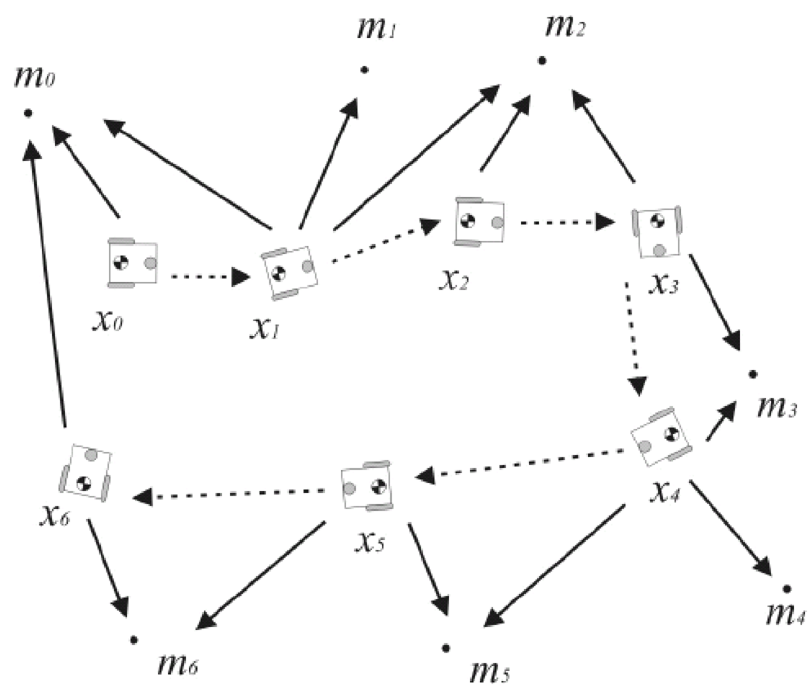


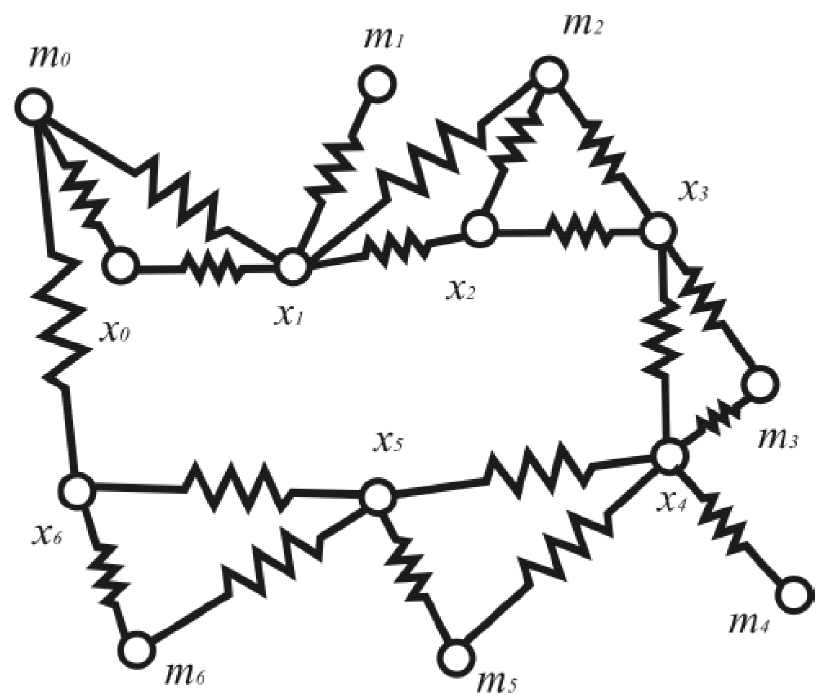
# Bundle Adjustment



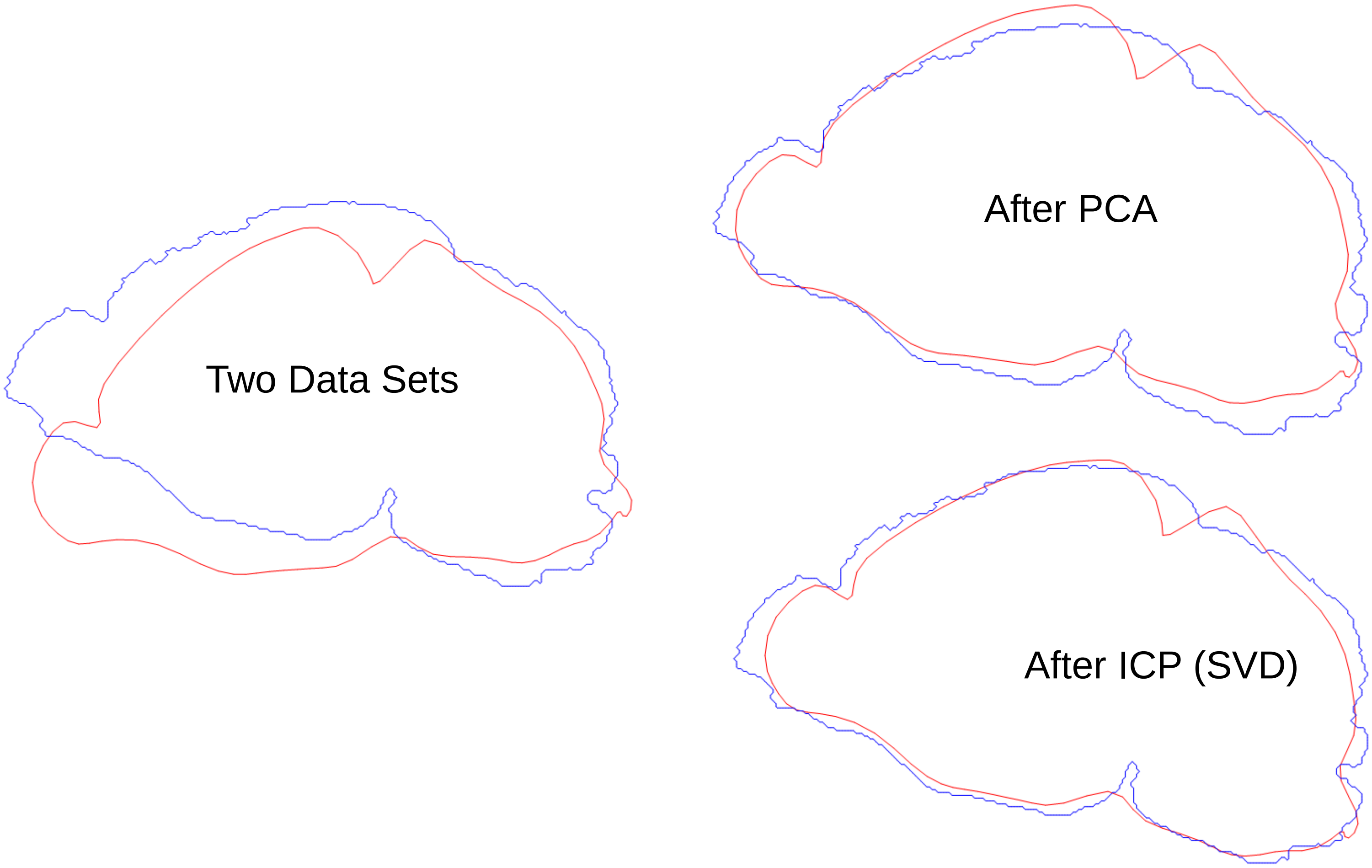



# Graph Optimization

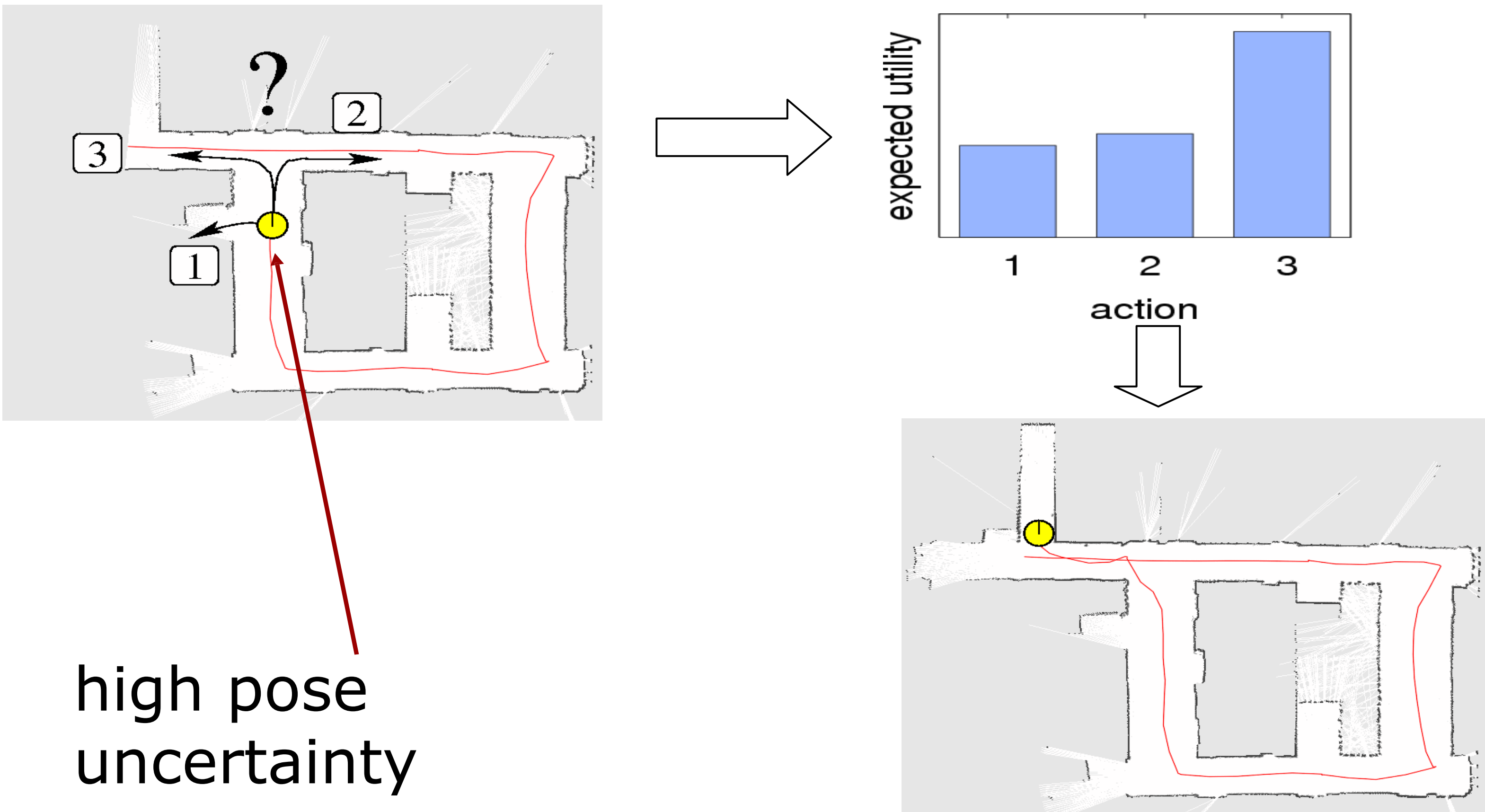


# Iterative Closest Points



# Information Gain Based Exploration



# Outlines

- Robot Types and Framework
- Problem Statement
- Related Areas
- History
- Optimization for Intelligent Robots
- Algorithms
- Platforms and Demos

# Husky A200

# Turtlebot2

# Turtlebot3

# OpenROV

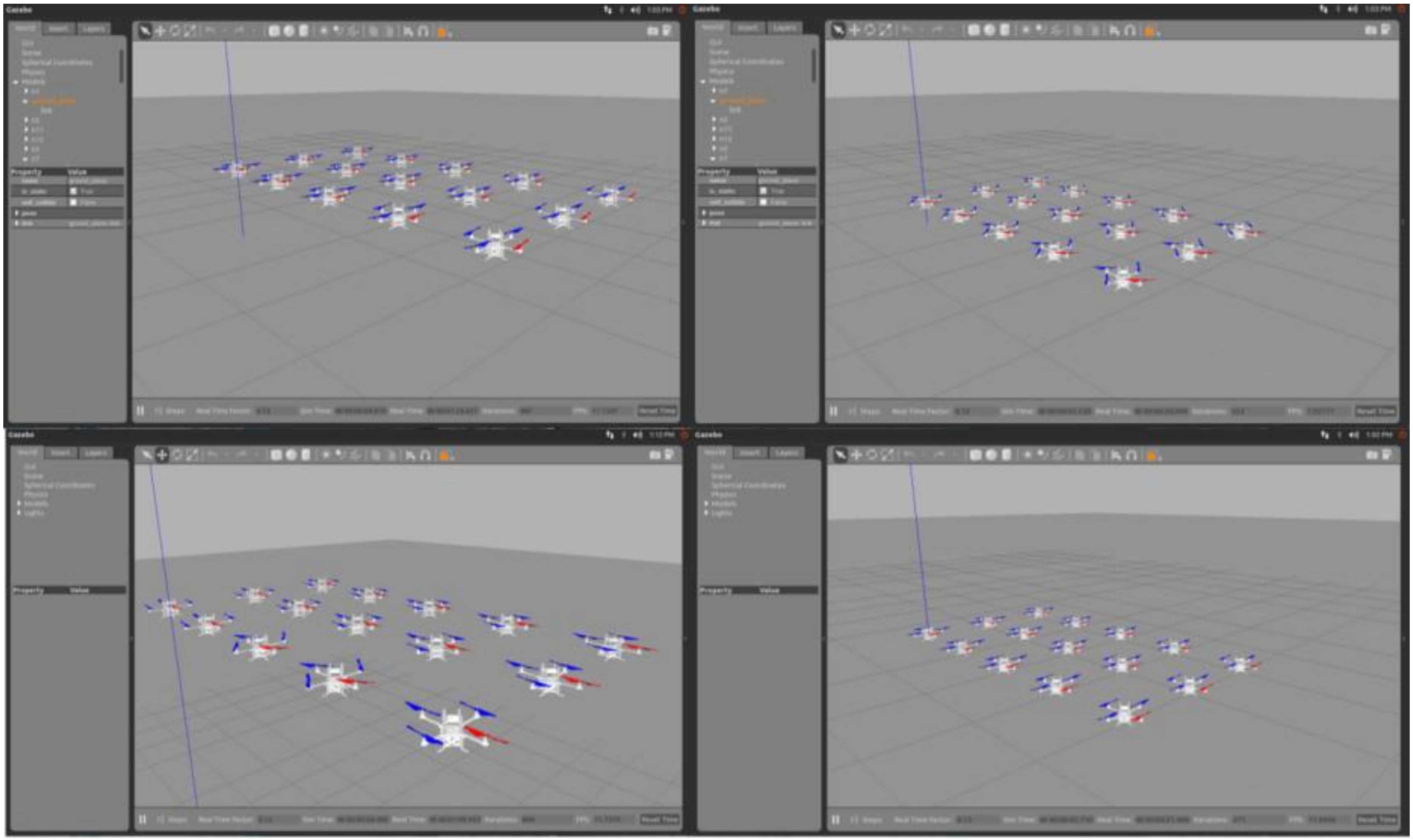
OPENROV
TrustFire
TR-008
CHARGE THREE
18650/25500
26650/26700
32650
NEW

# DJI M100

# Self-Driving Car

# Self-Driving Bus

# Simulation Environment: Gazebo



# Indoor Environment

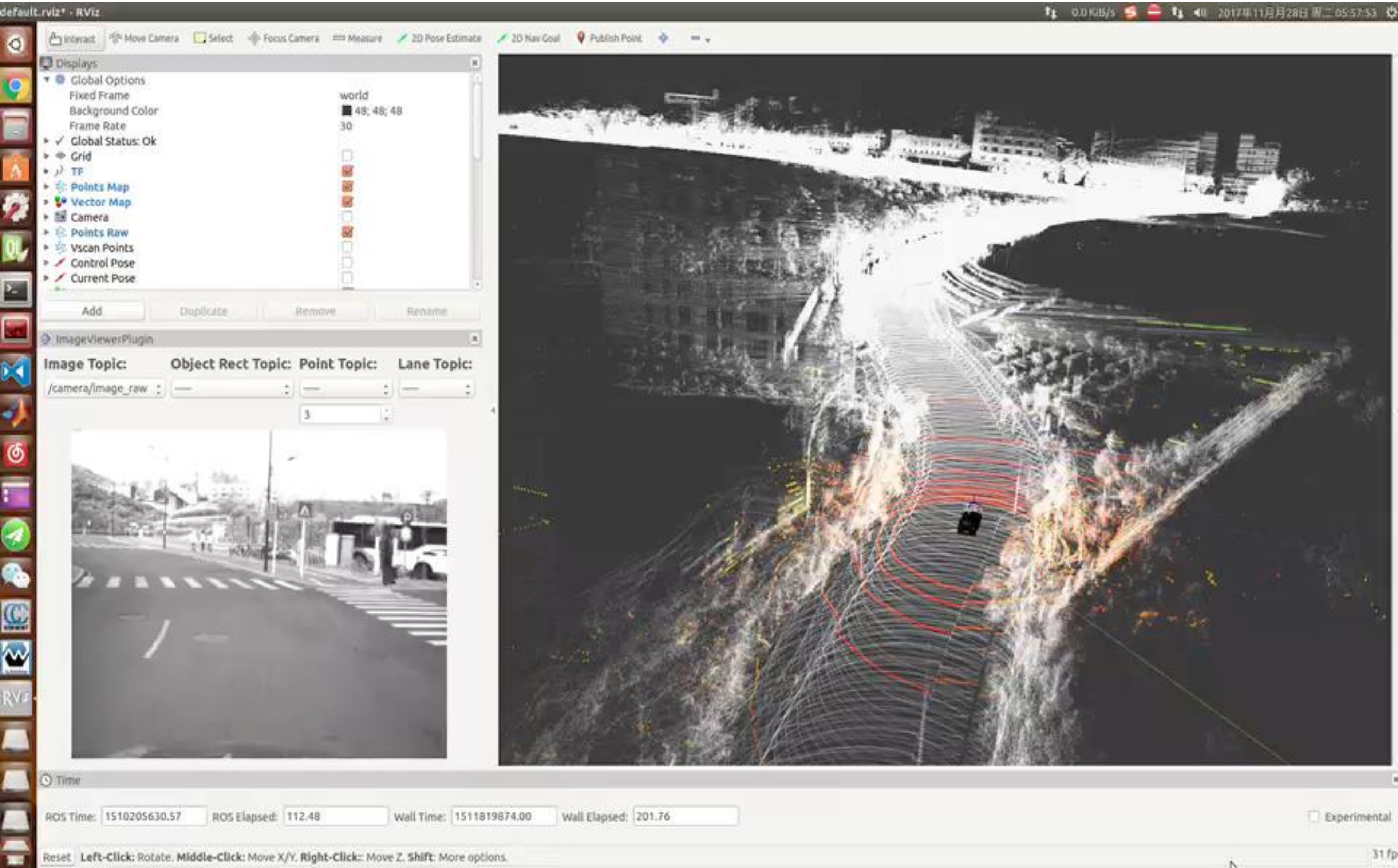
# Outdoor Environment

# 3D Reconstruction

# Simulation for Reinforcement Learning

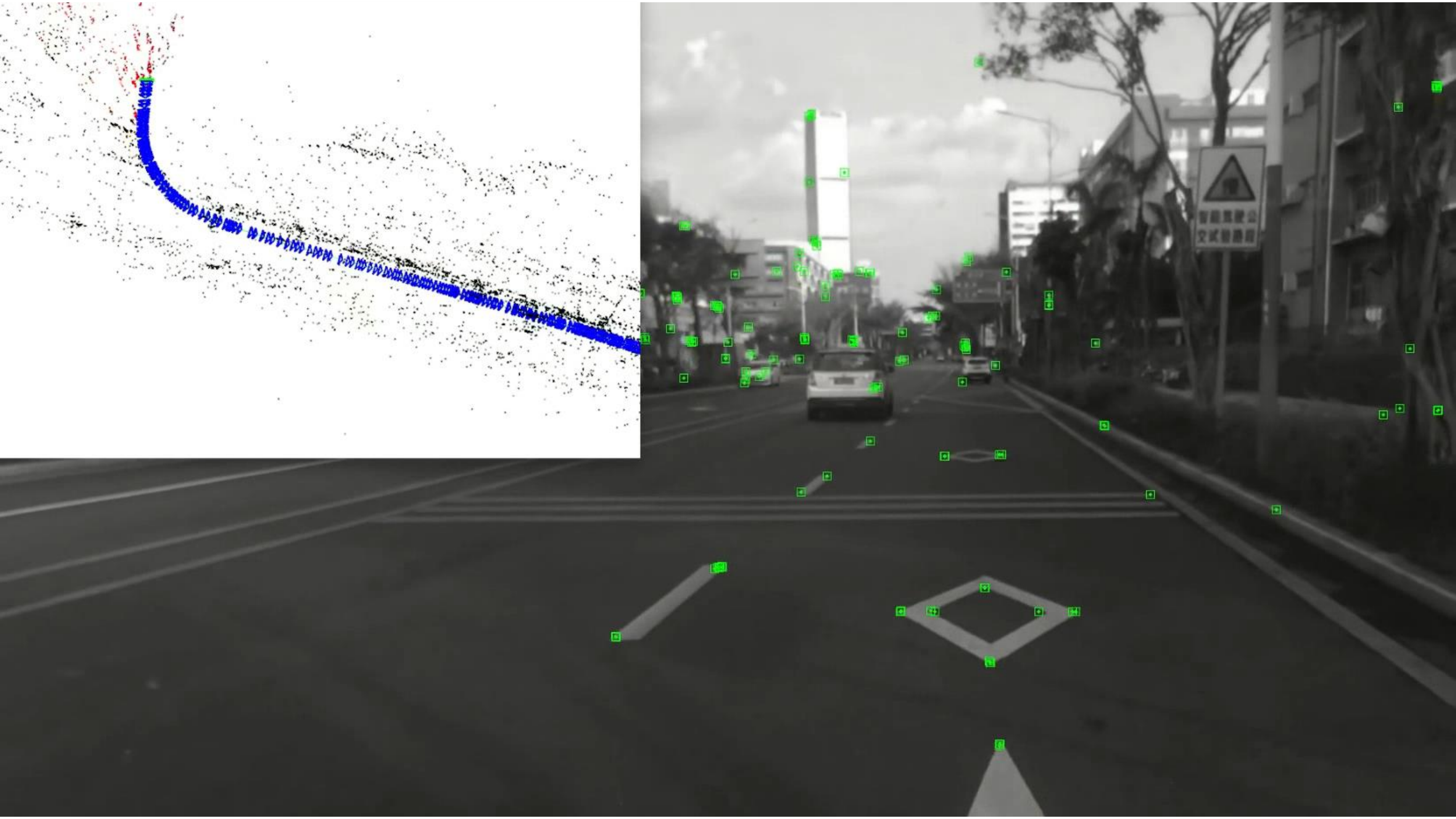
# Indoor SLAM Experiment

# Outdoor SLAM Experiment



# Outdoor Autonomous Driving

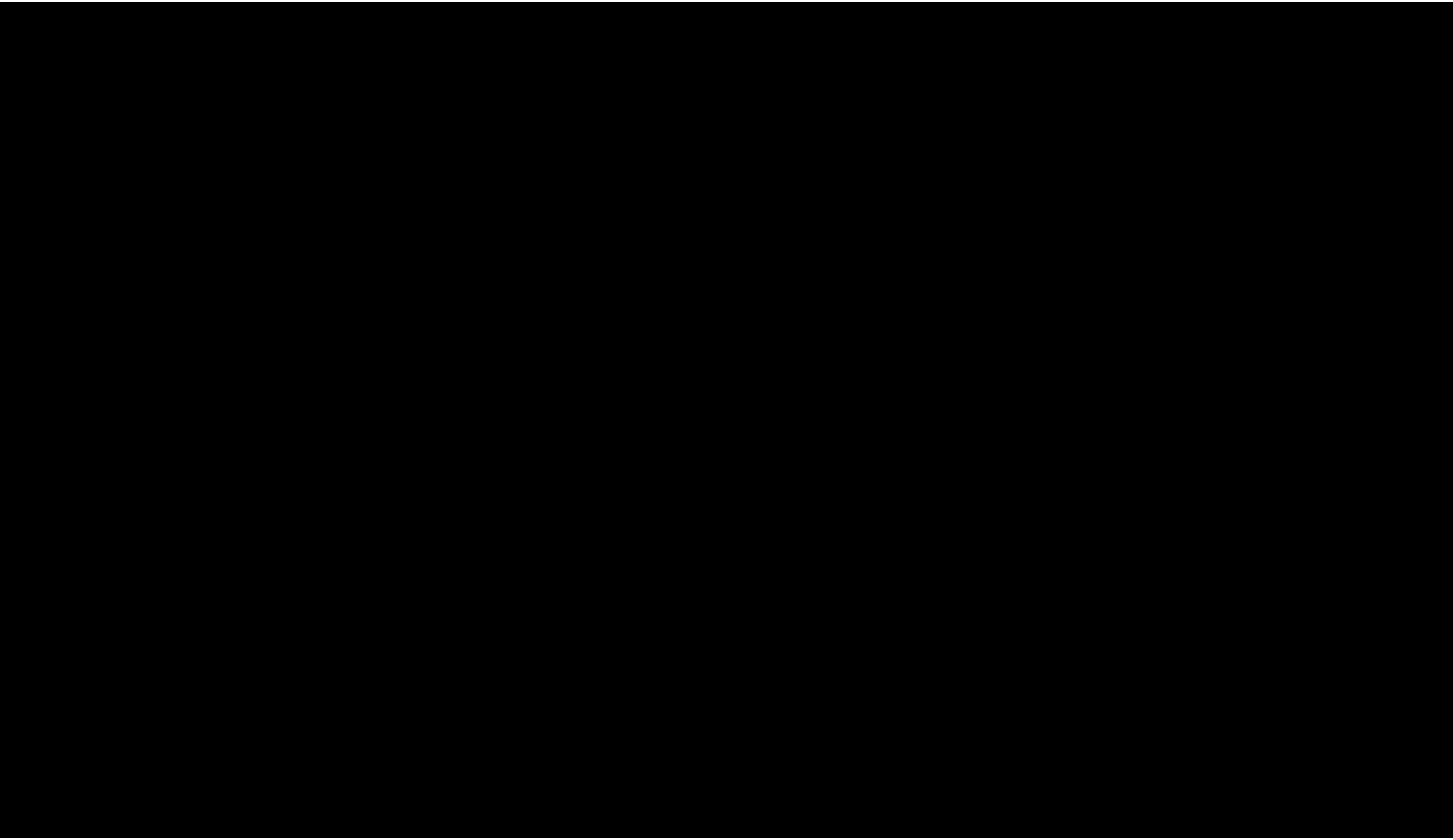
# Vision Based Odometry



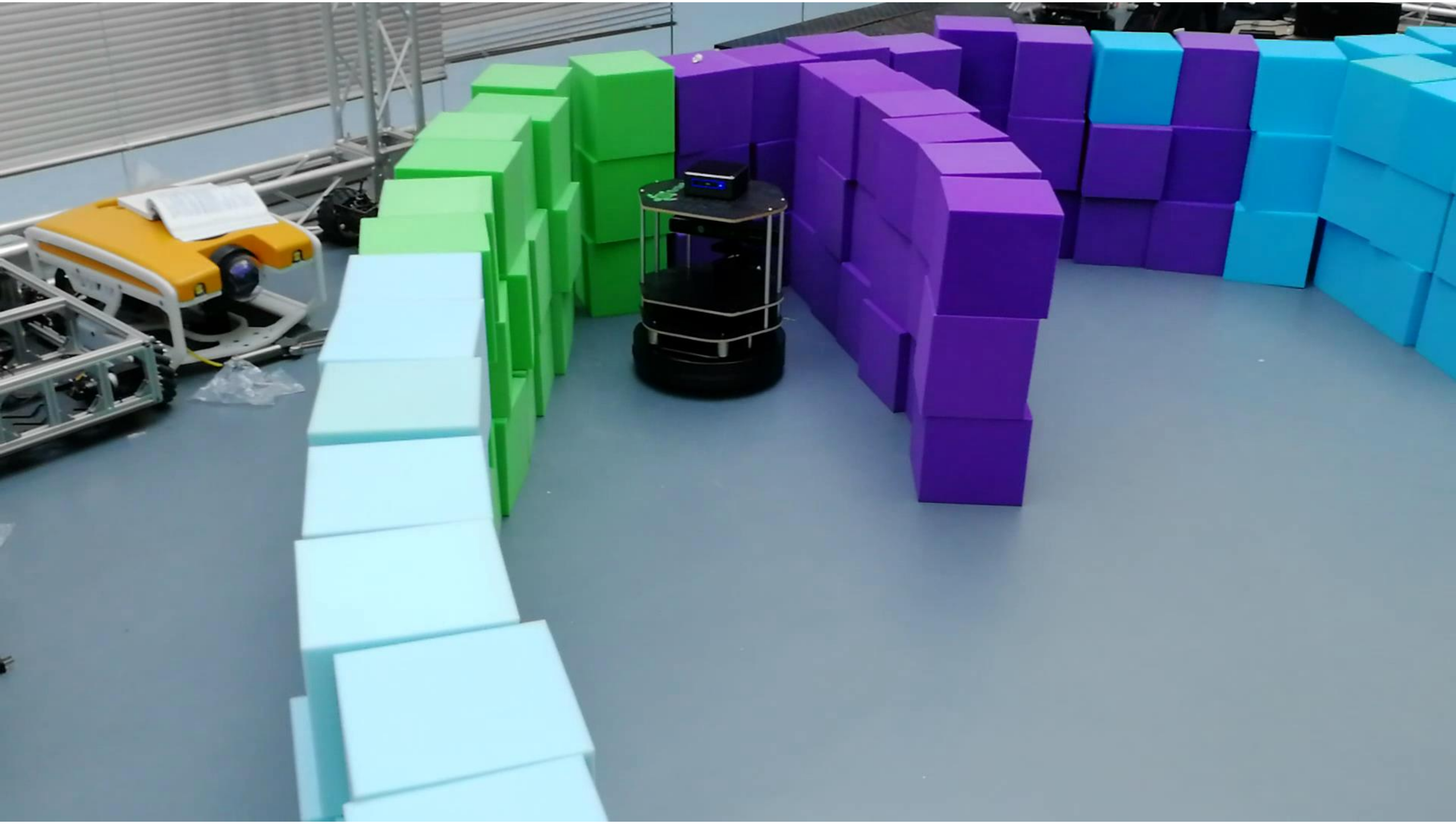
# Outdoor Autonomous Driving

# Final Project Example I

# Final Project Example II



# Final Project Example III



# Thanks !