Introduction

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Lecture 01

Robotic Exploration and Data Collection Planning

Overview of the Lecture

Part I

Part 1 – Course Organization

Course

- **Robotic Exploration and Data Collection Planning (REDCP)**
  `https://cw.fel.cvut.cz/wiki/courses/crl-courses/redcp/start`
- Selected topics from **B4M36UIR – Artificial Intelligence in Robotics**
  `https://cw.fel.cvut.cz/wiki/courses/uir`

prof. Ing. **Jan Faigl**, Ph.D. (`faiglj@fel.cvut.cz`)

- Center for Robotics and Autonomous Systems (CRAS)
  `http://robotics.fel.cvut.cz`
- **Computational Robotics Laboratory** (CRL)
  `http://comrob.fel.cvut.cz`

Course Goals

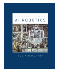
- Become familiar with robotics problems and notion of robotic information gathering.
  - Existing problems and solutions.
- Acquire experience on combining approaches in robotic exploration program.
  Tasks
- Acquire knowledge of robotic data collection planning.

Course Organization and Evaluation

- Selected topics on robotic exploration and data collection planning in 6 lectures.
  With 2-3 more lectures as an option.
- **Task 1** (t1-exploration) - Implementation of frontier-based exploration that combine six tasks.
  - `t1a-ctrl` – Open-loop robot motion control
  - `t1b-react` – Reactive obstacle avoidance
  - `t1c-plan` – Grid based path planning
  - `t1d-map` – Map building
  - `t1e-frontiers` – Determining frontiers as possible goal locations for exploration
  - `t1f-exploration` – Mobile robot exploration
  - Implement exploration pipeline with CoppeliaSim (and Python).
- **Task 2** (t2-tspn) - Implementation of the solver to the data collection planning.
  - `t2-tspn` – Close Enough Traveling Salesman Problem.
    Data collection planning
  - Implement unsupervised learning-based solver (in Python).
- Task(s) evaluation in January 2023.

Resources and Literature

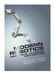
- Introduction to AI Robotics, *Robin R. Murphy*
  MIT Press, 2000
  Background and context



- The Robotics Primer, *Maja J. Mataric*
  MIT Press, 2007
  Background and context

- Planning Algorithms, *Steven M. LaValle*
  Cambridge University Press, 2006
  `http://planning.cs.uiuc.edu`

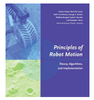
- Modern Robotics: Mechanics, Planning, and Control, *Kevin M. Lynch, Frank C. Park*
  Cambridge University Press, 2017



- **Lectures** – "comments" on the textbooks, slides, and **your notes**.
- **Selected research papers** – on particular topics providing furhter info.

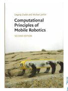
Further Books 1/2

- Principles of Robot Motion: Theory, Algorithms, and Implementations, *H. Choset, K. M. Lynch, S. Hutchinson, G. Kantor, W. Burgard, L. E. Kavraki and S. Thrun*
  MIT Press, Boston, 2005



- Introduction to Autonomous Mobile Robots, 2nd Edition, *Roland Siegwart, Illah R. Nourbakhsh, and Davide Scaramuzza*
  MIT Press, 2011

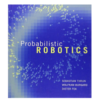
- Computational Principles of Mobile Robotics, *Gregory Dudek and Michael Jenkin*
  Cambridge University Press, 2010



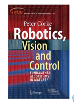
Further Books 2/2

- Robot Motion Planning and Control, *Jean-Paul Laumond*
  Lectures Notes in Control and Information Sciences, 2009
  `http://homepages.laas.fr/jpl/book.html`

- Probabilistic Robotics, *Sebastian Thrun, Wolfram Burgard, Dieter Fox*
  MIT Press, 2005
  `http://www.probabilistic-robotics.org/`



- Robotics, Vision and Control: Fundamental Algorithms in MATLAB, *Peter Corke*
  Springer, 2011
  `http://www.petercorke.com/RVC1/`



Communicating Any Issue Related to the Course

- Use e-mail for communication
  - Put REDCP to the subject of your message

Development Tools

- Python

  Eventually C/C++ (**gcc** or **clang**).
- CoppeliaSim – robotic simulator. `http://www.coppeliarobotics.com/`
- Sources and libraries provided by **Computational Robotics Laboratory**.
- Any other open source libraries.
- Information resources (IEEE Xplore, ACM, Science Direct, Springer Link)
  - *IEEE Robotics and Automation Letters (**RA-L**), IEEE Transactions on Robotics (**T-RO**), International Journal of Robotics Research (**IJRR**), Journal of Field Robotics (**JFR**), Field Robotics (**FR**), Robotics and Autonomous Robots (**RAS**), Autonomous Robots (**AuRo**), etc.*
  - *IEEE/RSJ International Conference on Intelligent Robots and Systems (**IROS**), Robotics: Science and Systems (**RSS**), IEEE International Conference on Robotics and Automation (**ICRA**), European Conference on Mobile Robots (**ECMR**), etc.*

Overview of the Lectures

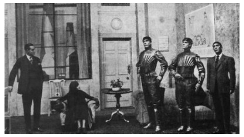
1. Course information, Introduction to (AI) robotics.
2. Robotic Paradigms and Control Architectures.
3. Path planning.
4. Robotic exploration.
5. Multi-goal planning.
6. Data collection planning.

- *Curvature-Constrained Data Collection Planning.* Optional
- *Randomized Sampling-based Motion Planning Methods.* Optional
- *Overview of the research in Computational Robotics Laboratory.* Optional

Part II

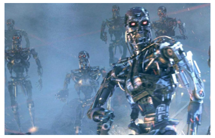
Part 2 – Introduction to Robotics

What is Understood as Robot?

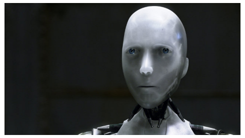


Rossum's Universal Robots (R.U.R)

Industrial robots



Cyberdyne T-800

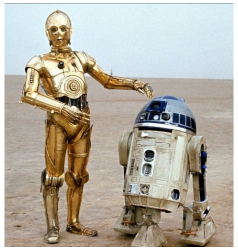


NS-5 (Sonny)

Artificial Intelligence (AI) is probably most typically understand as an intelligent robot.

Intelligent Robots

- React to the environment – sensing.
- Adapt to the current conditions.
- Make decision and new goals. As in robotic exploration.



- Even though they are autonomous systems, the behaviour is relatively well defined.
- Adaptation and ability to solve complex problems are implemented as algorithms and techniques of **Artificial Intelligence**.

  In addition to mechanical and electronical design, robot control, sensing, etc.

Stacionary vs Mobile Robots

- Robots can be categorized into two main groups.

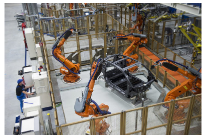
Stationary (industrial) robots

Mobile robots

- Stationary robots – defined (limited) working space, but efficient motion is needed.
  - Motion planning tasks is a challenging problem.
- Mobile robot – it can move, and therefore, it is necessary to address the problem of **navigation**, which a combination of localization, mapping, and planning.

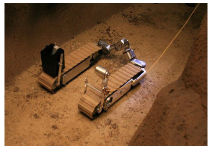
Stationary Robots

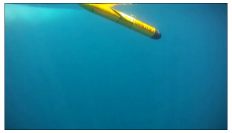
- Conventional robots needs separated and human inaccessible working space because of safety reasons.
- Collaborative robots share the working space with humans.

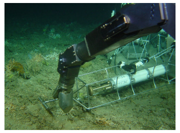


Types of Mobile Robots

- According to environment: ground, underground, aerial, surface, and underwater.
- Based on the locomotion: wheeled, tracked, legged, modular.







Challenges in Robotics

- Autonomous vehicles – cars, delivery, etc.
- Consumable robots – toys, vacuum cleaner, lawn mover, pool cleaner
- Robotic companions
- Search and rescue missions
- Extraterrestrial exploration
- Robotic surgery
- Multi-robot coordination

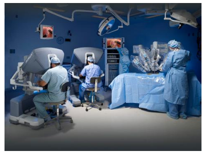
In addition to other technological challenges, new efficient AI algorithms have to be developed to address the nowadays and future challenges.

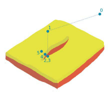
Robotic Surgery

- Evolution of Laparoscopic Surgery

  Complex operations with shorter postoperative recovery
- Precise robotic manipulators and teleoperated surgical robotic systems
- Further step is automation of surgical procedures.

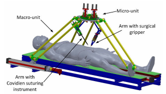
  One of the main challenges is planning and navigation in tissue.





Tissue model

Robotic arm of the Da Vinci surgical system



Concept of the surgical system

Surgical droid 2-1B

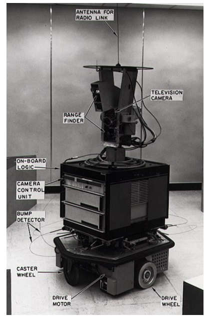
Artificial Intelligence and Robotics

Artificial Intelligence (AI) field originates in 1956 with the summary that a intelligent machine needs:

- Internal models of the world;
- Search through possible solutions;
- Planning and reasoning to solve problems;
- Symbolic representation of information;
- Hierarchical system organization;
- Sequential program execution.

  M. Mataric, Robotic Primer
- AI-inspired robot – Shakey

  Artificial Intelligence laboratory of Stanford Research Institute (1966–1972)
- Shakey – perception, geometrical map building, planning, and acting – early AI-inspired robot with purely deliberative control. See, e.g., https://www.youtube.com/watch?v=qXdn6ynwpiI



Robotics in REDCP

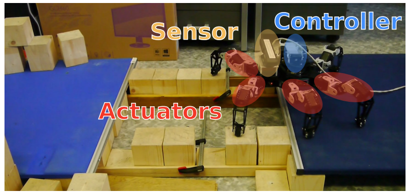
- Fundamental problems related to motion planning and mission planning with mobile robots.
- The discussed motion planning methods are general and applicable also into other domains and different robotic platforms including stationary robotic arms.
- **Robotics is interdisciplinary field**
  - Electrical, mechanical, control, and computer engineering;
  - **Computer science** filds such as machine learning, artificial intelligence, computational intelligence, machine perception, etc.
  - Human-Robot interaction and cognitive robotics are also related to psychology, brain-robot interfaces to neuroscience, robotic surgery to medicine, etc.

*In REDCP, we will touch a small portion of the whole field, mostly related to motion planning and mission planning that can be "encapsulated" as **robotic information gathering**.*

What is a Robot?

A robot is an autonomous system which exists in the physical world, can sense its environment, and can act on it to achieve some goals.

- The robot has a physical body in the physical world – **embodiment**.
- The robot has **sensors** and it can **sense**/**perceive** its environment.
- A robot has effectors and actuators – it can **act** in the environment.
- A robot has **controller** which enables it to be **autonomous**.



Embodiment

- The robot body allows the robot to act in the physical world.

  E.g., to go, to move objects, etc.
- Software agent is not a robot.
- Embodied robot is under the same physical laws as other objects.
  - Cannot change shape or size arbitrarily.
  - It must use actuators to move.
  - It needs energy.
  - It takes some time to speed up and slow down.
- Embodied robot has to be aware of other bodies in the world.
  - Be aware of possible collisions.
- The robot body influences how the robot can move.

  Notice, faster robots look smarter.

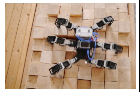
Sensing / Perception

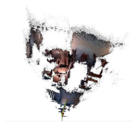
- Sensors are devices that enable a robot to perceive its physical environment to get information about itself and its surroundings.
- **Exteroceptive** sensors and **proprioceptive** sensors.
- Sensing allows the robot to know its **state**.
- State can be **observable**, **partially observable**, or **unobservable**.
  - State can be **discrete** (e.g., on/off, up/down, colors) or **continuous** (velocity).
  - **State space** consists of all possible states in which the system can be.
    - **Space** refers to all possible values.
  - **External state** – the state of the world as the robot can sense it.
  - **Internal state** – the state of the robot as the robot can perceive it.

    E.g., remaining battery.

Sensors

- **Proprioceptive sensors** – measure internal state, e.g., encoders, inclinometer, inertial navigation systems (INS), compass, but also Global Navigation Satellite System (GNSS), e.g., GPS, GLONASS, Galileo, BeiDou.
- **Exteroceptive (proximity) sensors** – measure objects relative to the robot.
  - **Contact sensors** – e.g., mechanical switches, physical contact sensors that measure the interaction forces and torques, tactile sensors etc.
  - **Range sensors** – measure the distance to objects, e.g., sonars, lasers, IR, RF, time-of-flight.
  - **Vision sensors** – complex sensing process that involves extraction, characterization, and information interpretation from images.



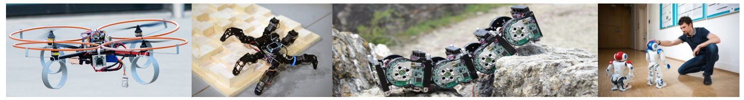


Action

- **Effectors** enable a robot to take an action.
  - They use underlying mechanisms such as muscles and motors called **actuators**.
- Effectors and actuators provide two main types of activities.
  - **Locomotion** – moving around;

    Mobile robotics – robots that move around.
  - **Manipulation** – handling objects.

    Robotic arms
- Locomotion mechanisms – wheels, legs, modular robots, but also propellers etc.

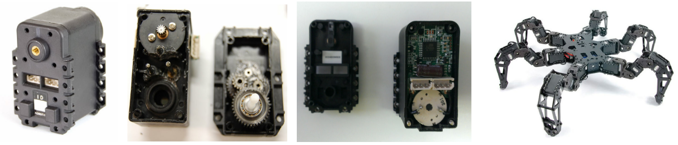


With more and more complex robots, a separation between mobile and manipulator robots is less strict and robots combine mobility and manipulation.

Effectors and Actuators

- **Effector** – any device on a robot that has an effect on the environment.
- **Actuator** – a mechanism that allows the effector to execute an action or movement, e.g., motors, pneumatics, chemically reactive materials, etc.
- Electric motors – Direct-Current (DC) motors, gears.
  - **Servo motors** – can turn their shaft to a specific position.

DC motor + gear reduction + position sensor + electronic circuit to control the motor.

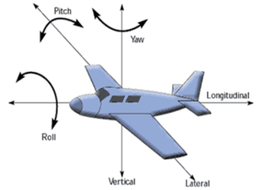


Hexapod with 3 servo motors (joints) per each leg has 18 servo motors in the total.

Degrees of Freedom (DOF)

- **Degree of Freedom (DOF)** is the minimal required number of independent parameters to completely specify the motion of a mechanical system. *It defines how the robot can move.*

  In 3D space, a body has usually 6 DOF (by convention).
  - **Translational DOF** – x, y, z.
  - **Rotational DOF** – *roll*, *pitch*, and *yaw*.

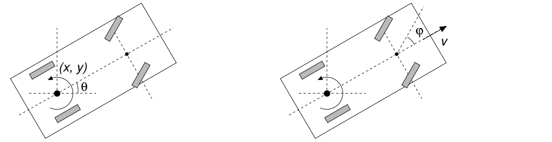


- **Controllable DOF (CDOF)** – the number of the DOF that are controllable, i.e., a robot has an actuator for such DOF.

DOF vs CDOF

- If a vehicle moves on a surface, e.g., a car, it actually moves in 2D.
- The body is at the position $(x, y) \in \mathbb{R}^2$ with an orientation $\theta \in \mathbb{S}^1$.
- A car in a plane has DOF = 3, (x, y, θ) but CDOF=2, (v, φ).

Only forward/reverse direction and steering angle can be controlled.

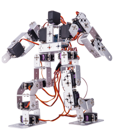


That is why a parallel parking is difficult.

- A car cannot move in an arbitrary direction, but 2 CDOF can get car to any position and orientation in 2D.
- To get to a position, the car follows a continuous trajectory (path), but with discontinuous velocity. *Uncontrollable DOF makes the movement more complicated.*

Ratio of CDOF to the Total DOF

- The ratio of Controllable DOF (CDOF) to the Total DOF (TDOF) represents how easy is to control the robot movement.
- **Holonomic** (CDOF=TDOF, the ratio is 1) – holonomic robot can control all of its DOF.
- **Nonholonomic** (CDOF<TDOF, the ratio < 1) – a nonholonomic robot has more DOF that it can control. *E.g., a car.*
- **Redundant** (CDOF>TDOF, the ratio > 1) – a redundant robot has more ways of control.



17 CDOF

6 DOF Hexapod

24 TDOF, 18 CDOF Hexapod walking robot

Locomotion

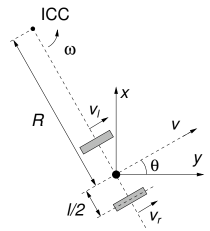
- **Locomotion** refers how the robot body moves from one location to another location.

  From the Latin Locus (place) and motion.
- The most typical effectors and actuators for ground robots are wheels and legs.
- Most of the robots need to be stable to work properly.
  - **Static stability** – a robot can stand, it can be static and stable.

    Biped robots are not statically stable, more legs make it easier. Most of the wheeled robots are stable.
  - **Statically stable walking** – the robot is stable all the times. *E.g., hexapod with tripod gait.*
  - **Dynamic stability** – the body must actively balance or move to remain stable, the robots are called dynamically stable. *E.g., inverse pendulum.*

Locomotion – Wheel Robots

- One of the most simple wheeled robots is **differential drive** robot.
  - It has two drived wheels on a common axis.
  - It may use a castor wheel (or ball) for stability.
  - It is nonholonomic robot. *Omnidirectional robot is holonomic robot.*

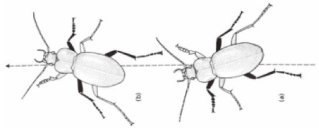


- v_l and v_r are velocities along the ground of the left and right wheels, respectively.
- $\omega = \frac{v_r - v_l}{l}$, $R = \frac{l}{2}\frac{v_l + v_r}{v_r - v_l}$
- For $v_l = v_r$, the robot moves straight ahead. *R* is infinite.
- For $v_l = -v_r$, the robot rotates in a place. *R* is zero.
- Simple motion control can be realized in a turn-move like schema.

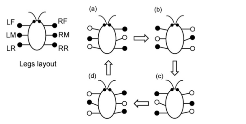
Further motion control using path following or trajectory following approaches with feedback controller based on the position of the robot to the path / trajectory.

Locomotion – Legged Robots (Gaits)

- **Gait** is a way how a legged robot moves.
- A gait defines the order how the individual legs lift and lower and also define how the foot tips are placed on the ground.
- Properties of gaits are: stability, speed, energy efficiency, robustness (how the gait can recover from some failures), simplicity (how complex is to generate the gait).
- A typical gait for hexapod walking robot is **tripod** which is stable as at least three legs are on the ground all the times.



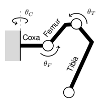
Gullan et al., The Insects: An outline of entomology, 2005

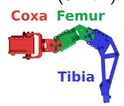


Iida et al. 2008

Locomotion of Hexapod Walking Robot

- Six identical leg each consisting of three parts called **Coxa**, **Femur**, and **Tibia** (3 DoF).



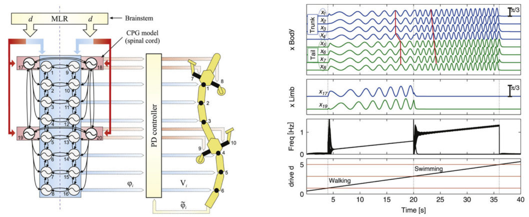


- The movement is a coordination of the **stance** and **swing** phases of the legs defined by the gait, e.g., tripod.
- A **stride** is a combination of the leg movement with the foot tip on the ground (during the **stance phase**) and the leg movement in a particular direction (in the **swing phase**) within one **gait cycle**.
- T_{Stance}, T_{Swing}, and $T_{Stride} = T_{Stance} + T_{Swing}$ defines the **duty factor** $\beta = T_{Stance}/T_{Stride}$.

  Tripod $\beta = 0.5$
- Various gaits can be created by different sequences of stance and swing phases.

Central Pattern Generator (CPG)

- **Central Pattern Generators (CPGs)** – are neural circuits to produce rhythmic patterns for various activities, i.e., locomotor rhythms to control a periodic movement of particular body parts.
- Salamander CPG with 20 amplitude-controlled phase oscillators.



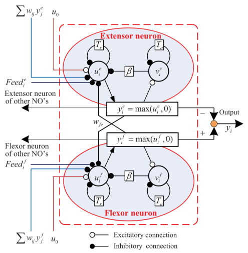
Auke Jan Ijspeert, Neural Networks, 2008

Example of Rhythmic Pattern Oscillator

- Matsuoka oscillator model based on biological concepts of the extensor and flexor muscles.
- Van der Pol oscillator

$$\frac{d^2x}{dt^2} - \mu(1-x^2)\frac{dx}{dt} + x = 0.$$

- The rhythmic patterns define the trajectory of the leg end point (foot tip).
- Joint angles can be computed from the foot tip coordinates using the **Inverse Kinematics**.



Matsuoka, K. (1985). Sustained oscillations generated by mutually inhibiting neurons with adaptation. Biological Cybernetics 52, 367—376

An example of simple CPG to control hexapod walking robot will be shown during the labs.

Control Architectures

- A single control rule may provide simple robot behaviour.

  Notice, controller can be feed-forward (open-loop) or feedback controller with vision based sensing.
- Robots should do more than just avoiding obstacles.
- The question is "How to combine multiple controllers together?"
- **Control architecture** is a set of guiding principles and constraints for organizing the robot control system.
  - Guidelines to develop the robotic system to behave as desired.

    It is not necessary to know control architectures for simple robotic demos and tasks. But it is highly desirable to be aware of architectures for complex robots.

Summary of the Lecture

Topics Discussed

- Information about the Course
- Overview of robots, robotics, and challenges
  - Robot – Embodied software agent
  - Sensor, Controller, Actuators
  - Degrees of Freedom (DOF) and Controllable DOF
  - Mobile Robot Locomotion
  - Locomotion Gaits for Legged Robots
  - Central Pattern Generator
- Next: Robotic Paradigms and Control Architectures