# Simulation, Analysis, and Validation of Computational Models

— Case Studies I —

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# Overview

- Case studies
- Robotics
- Robots in recycling, delivery and as pets

# Case studies

- Case studies are a way to learn about practical problems
  - What aspects need to be included (in addition to general or theoretical knowledge)
  - What interaction among these aspects needs to be considered?
- How to integrate existing knowledge and models
  - Do dynamical systems help to model a system?
  - What other tools are available?
- How to find out whether the model is valid?
  - What observations, tests, or measurement need to be made?
  - Under what conditions should these be made?

* *Case study* doesn't come with a formal definition

# Case study research

- One instance of an identifiable contemporary *phenomenon* or *intervention*
- Empirical inquiry within its real–life context (field study studies only the context)
- Boundary between phenomenon and context cannot be clearly specified
- Investigators not taking an active role in the case investigated (otherwise: *action research* or *participant observation*)
- Shouldn't be merely a toy problems nor a small-scale evaluation
- Observation of several aspects

Wohlin (2021) Case study research in software engineering. Inf. Softw. Technol. 133, 106514.

Runeson e.a. (2012) Case study research in software engineering, Wiley Publishing.
Wohlin & Rainer (2022) Is it a case study? J. Syst. & Softw. **192**, 111395.

# Case studies: Additional remarks

- Qualitative work (noncomparable observations)
  vs. quantitative observations (comparable observations)
- *Cross-case* studies use a small number of instances
- Case selection
  - Not meant to be representative, but outlining the spaces that is to be represented.
  - Questioning existing theories (Proto-general, not "atheoretic")
  - Hypothesis-generating

A.L. George (2005) Case studies and theory development in the social sciences. Belfer Center for Science and Int. Affairs.

- Models typically result from a case study, but need more than one case study to be established.

# Robot modelling

Robot modelling is comparatively easy, it includes

1. Description of hardware architecture
2. Characteristics of sensors, processors, actuators
3. Control principles, energy supply, communication channels
4. Software architecture

0. [1]Support, mission, time frame, environment (incl. noise), purpose, evaluation ($W^5H$)

[1]One would usually start with the systems engineering tasks.

# Describing robots

- A *robot manipulator* consists of a sequence of rigid bodies (links) interconnected by means of articulations (joints); a manipulator is characterised by an arm that ensures mobility, a wrist that confers dexterity, and an end-effector that performs the task required of the robot.

B. Siciliano (2008) Robotics: Modelling, Planning and Control. Springer.

- A legged robot follows this definition (replace *wrist* $\rightarrow$ *foot*) if we forget about the end-effector as the task is just the mobility.
- Wheeled robots don't fit the definition perfectly, but are not more difficult to model
- Modelling can be challenging in other types of robots: AUV, drones (UAV), soft robots, biorobots and prostheses, nano-robots, autonomous things, smart matter etc.

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*We'll start with the technical aspects anyway.

# Modelling robot manipulator

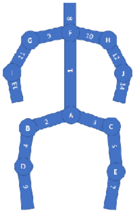
A robot manipulator is usually a kinematic chain, consisting of “stacked” pendula with

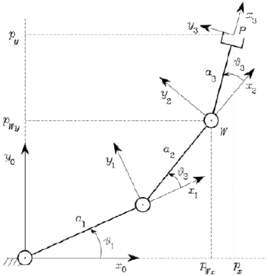
- hinge joints (2D)
- ball joints (3D)

as pivots. Each pendulum (Lect. 3) is damped and controlled and form a

$$I\ddot{\vartheta} + a\,m\,g\sin\vartheta + k\dot{\vartheta} = \tau_{\text{motor}}$$

In addition, there can be controllable linear degrees of freedom, wheels, belts, Bowden cables, or more complex linkage





To model use e.g. Webots or Peter Corke’s Robotics Toolbox

# Towards a robot model

Kinematics: Geometry of motion of objects without reference to the forces that cause the motion.

Linkage, Number and types of joints, open or closed kinematic chains, ranges of angles, lengths of bars etc.

Dynamics: Action of motion concerned with the motion of bodies under the action of forces.

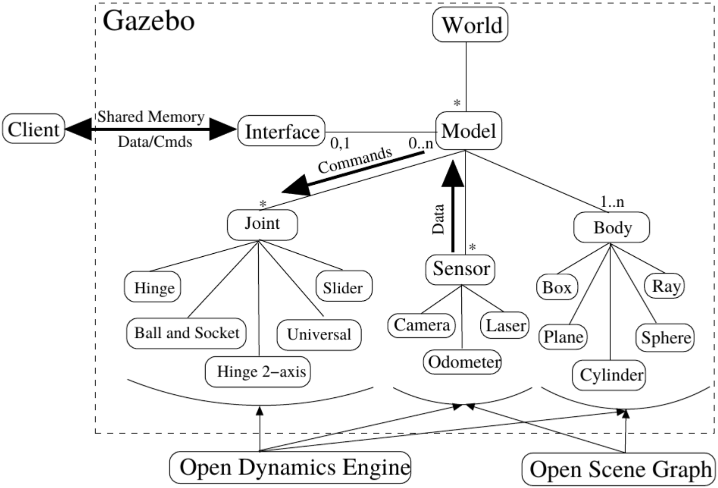
Types of motors, motor placement, mass distribution (incl. cables, sensors, casing), payload, noise etc.

Control: The way to change system dynamics.

Control objective, feedback loops, sensors, time delays, prediction etc.

Previously we have considered mainly autonomous systems, while practically non-autonomous systems are the standard because environmental influences are important.

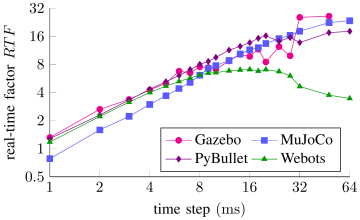
# Gazebo robotics simulator: Simulate before you build




Koenig & Howard (2004) Design and use paradigms for gazebo, an open-source multi-robot simulator. IROS 3, 2149-2154.

# Comparing robotics simulators

- Webots: 3D robot simulator (ODE)
- Gazebo: 2D/3D robotics simulator (ODE)
- PyBullet: physics engine Simulates collisions and soft and rigid body dynamics.
- MuJoCo: physics engine: Multi-Joint dynamics with Contact (now DeepMind)




| | | Server | | Mobile workstation | | Notebook | |
|---|---|---|---|---|---|---|---|
| | | CPU | *RTF* | CPU | *RTF* | CPU | *RTF* |
| Gazebo | robot | 273.0 % | 4.3 | 264.4 % | 4.4 | (11.9 %) | 2.3 |
| | spheres | 223.1 % | 1.1 | 208.7 % | 1.4 | 213.2 % | 0.8 |
| MuJoCo | robot | 116.3 % | 2.4 | 100.8 % | 2.8 | 103.1 % | 2.1 |
| | spheres | 113.4 % | 0.6 | 99.8 % | 0.8 | 102.8 % | 0.6 |
| PyBullet | robot | 119.3 % | 0.7 | 102.0 % | 0.8 | 104.0 % | 0.6 |
| | spheres | 118.0 % | 1.1 | 100.7 % | 1.3 | 103.8 % | 1.0 |
| Webots | robot | 124.3 % | 1.8 | 105.6 % | 1.7 | 109.1 % | 1.3 |
| | spheres | 120.7 % | 1.2 | 103.8 % | 1.2 | 103.3 % | 0.5 |

For details see: Körber (2021) Comparing Popular Simulation Environments in the Scope of Robotics ... arXiv:2103.04616v1

# Further aspects of dynamics in robotics

Dynamics in robotics is not limited to the kinematic chains

- Stability, optimality and robustness of control
- Movement in the environment (e.g. potential field method)
- Internal models for Prediction of effects of changes in the environment: mechanical support, moving objects, wind, water current, heat, ...
- Internal models for prediction of consequences of own actions e.g. for planning
- Definition of subgoals
- Interaction with other robots and humans
- Flexibility and efficiency by instability
- Robot learning and exploration: Data is based on trajectories and tends to be highly correlated and conservative (i.e. usually no data on what the robot cannot yet do)

Khansari-Zadeh, S.M. & Billard, A., (2011) Learning stable nonlinear dynamical systems with Gaussian mixture models. IEEE Transact. Robotics **27**, 943-957.

# Support, mission, schedule, environment, purpose, evaluation

**Who** Diverse expertise required

**What** High-level task specification[2]

**When** From decades to minutes

**Where** Knowledge and control of the environment comes with a cost

**Why** From academic research to market driven applications

**How** Effective, efficient, robust, minimal side effects, welcomed

[2] What was described above is part of this point.

# Industrial robotics (before 4.0)

**Who** Minimal human support (during standard operation), and specialists for the items below

**What** Tasks are an individual production step

**When** Short repetitive cycles (installation is difficult but human controlled)

**Where** Environment is typically fully under control

**Why** Purpose varies: large numbers — high quality (and many other business models)

**How** Evaluation: Testing, technical checks, customer service, market research

Industry 4.0 (WEF, since about 2015): Aspects are merging towards more integral and flexible processes, AI, autonomisation, cyber-physical systems, cognitive computing etc.

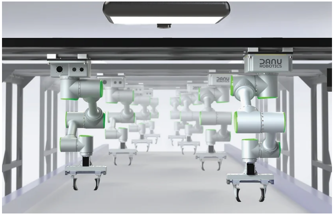
Industry 5.0 (EU Initiative): Sustainable, human-centric and resilient industry.

# Example: Waste separation

Danu Robotics: Machine learning for efficient and effective recycling

- AI guided computer vision system to extract bounding boxes
- Modular, multi-picker system for plastic packaging and aluminium cans.
- Learning system to coordinate vision and grasping
- Evaluation based on preparation, rates, quality and interruptions


Municipal recycling facilities, Montgomery County, MD, 2007, USEPA (Wikipedia)




https://www.danurobotics.com

# Modelling challenges: Waste separation

- Modelling recyclable waste: Statistical modelling (results depend on culture, waste management) to identify typical proportions, shapes, and recognition rates
- Robot modelling: Robot simulator can try various robot configuration (serial or parallel manipulator) and end-effectors (grasp, suction, piercing, sifting, swirling, magnetic lift)
- Control model: Movement primitives based control can be useful to simplify learning tasks
- Deep neural network models: Implicit models for handling pieces (NN-based policies) and continuous improvement (RL)

# Example: Self-driving cars

At full level of automation the system controls the vehicle under all conditions. with an error rate significantly below $10^{-9}$ per decision.
Models of many aspects of the environment.


| | | | | |
|---|---|---|---|---|
| Customer definition | Eyes-on Hands-on | Eyes-on Hands-off | Eyes-off Hands-off | No driver (Robotaxi) |
| | Driver Present | | | Tele-Operations |
| Safety MRM | Based on driver | Based on driver<br>Driver Monitoring System needed | Full MRM capability is mandatory<br>- Stopping safely on the shoulder of the road<br>- Stop-in-lane is not safe enough | |
| Non-safety MRM (deadlocks)<br><br>* MRM- Minimum Risk Maneuver | Based on driver | | | Tele-Operations |

# Example: Delivery robots

- Mission based on maps and local sensing at low speed
- High-level organisation is known
- Area of operation in safe environments (campus)

# Modelling challenges: Self-driving cars and delivery robots

Up-to-date maps as models of the (street-)world

How do weather conditions affect optimal driving?

Environment modelling:

- Other drivers
- Cyclists, pedestrians, animals
- Decreased attention (?)

Many unclear situation exists, that are critical even though being largely theoretical.

Safety vs. efficiency

Responsibility of producer

Meaningful behaviour in single car can become unstable in multi-robot systems

# Example: Pet robots

- Robotic platform
- Cognitive abilities
- Emotional dynamics
- Needs and desires

By Morgan from Montreal, Quebec, Canada 186.365 - July 5, 2010. curid=117938962

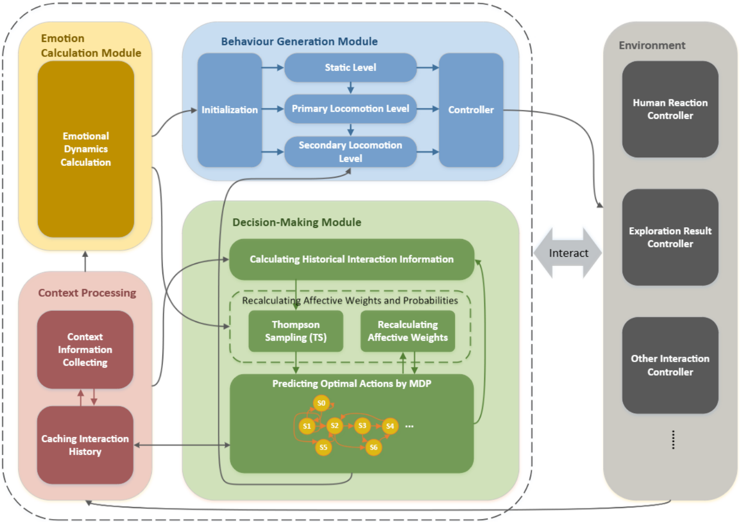
A pet should know its home environment and the people that are living there, too.

It should adapt to the family, and maintain models to plan, and to anticipate.

In pet robots not so much the final state, but the learning process itself is of interest.

Because of this and the special environment modelling and simulation is difficult.

# Modelling in controlling a robotic pet




Preliminary cognitive-affective control architecture.

# Discussion

- Robots are working in the real world, so a (more or less precise) model of the environment is required.
- A high degree of realism, the need for strong risk reduction, difficult learning tasks, large sets of robots, complex materials and environments are challenging for simulations.

# Conclusion

- Simulation of component can help to design the system step by step
- Robotic simulations help to prepare real-robot experiments
- They can also help to scale up the system after single-robot experiments have been made.
- Traditional robots are relatively easy to simulate, so self-models for prediction and planning are typical.
- Robot simulations are a critical step in business cases.

# Next topics

- Case studies II: Finance and social systems
- Lab II: Networks
- Case studies III: Weather and climate
- Lab III: Adaptive models