Robotic Paradigms and Control Architectures

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Lecture 02

Robotic Exploration and Data Collection Planning

Overview of the Lecture

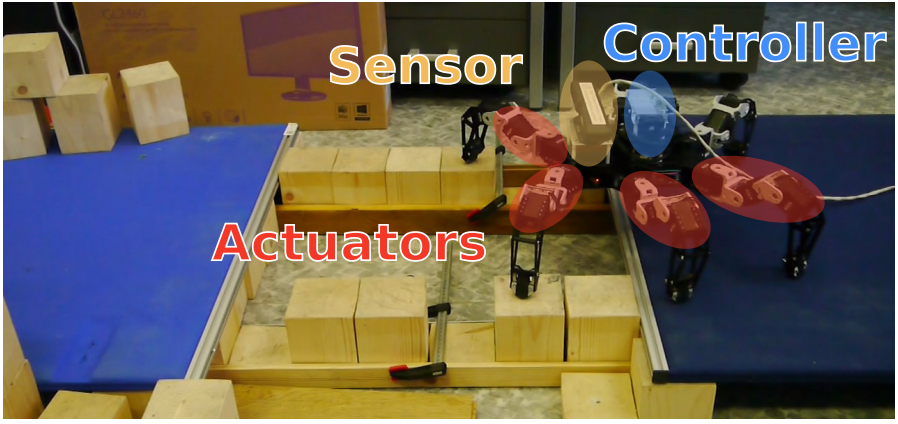
- Part 1 – Robotic Paradigms and Control Architectures
  - Robotics Paradigms
  - Hierarchical Paradigm
  - Reactive Paradigm
  - Hybrid Paradigm
  - Example of Collision Avoidance
  - Robot Control

Part I

Part 1 – Robotic Paradigms and Control Architectures

Robot

- A robot perceives an environment using **sensors** to **control** its **actuators**.



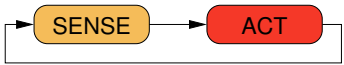
- The main parts of the robot corresponding to the primitives of robotics: **Sense**, **Plan**, and **Act**.
- The primitives form a **control architecture** that is called **robotic paradigm**.

Robotic Paradigms

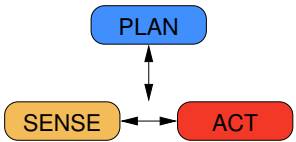
- **Robotic paradigms** define relationship between the robotics primitives: **Sense**, **Plan**, and **Act**.
- Three fundamental paradigms have been proposed.

1. **Hierarchical paradigm** is a purely deliberative system.

2. **Reactive paradigm** represents reactive control.



3. **Hybrid paradigm** combines reactive and deliberative.



Hierarchical Paradigm

- The robot senses the environment and creates the "world model".

  A "world model" can also be an a priori available, e.g., prior map.
- Then, the robot plans its action and executes it.

- The advantage is in ordering the relationship between the primitives.
- It is a direct "implementation" of the first AI approach to robotics.
  - Introduced in Shakey, the first AI robot (1967-70).
- It is **deliberative architecture**.
  - It uses a generalized algorithm for planning.
  - *General Problem Solver* – STRIPS

    Stanford Research Institute Problem Solver
- It works under the **closed world assumption**.
  - The world model contains everything the robot needs to know.

Disadvantages of the Hierarchical Model

- Disadvantages are related to planning and its **computational requirements**.
- Planning can be very slow and the "global world" representation has to contain further all information needed for planning. Sensing and acting are always disconnected.
- The "global world" representation has to be up-to-date.
  - The world model used by the planner has to be frequently updated to achieve a **sufficient accuracy** for the particular task.
- A general problem solver needs many facts about the world to search for a solution.
- Searching for a solution in a huge search space is quickly computationally intractable, and the problem is related to the so-called **frame problem**.
  - Even simple actions need to reason over all (irrelevant) details.
- **Frame problem** is a problem of representing real-world situations to be computationally tractable. *Decomposition of the world model into parts that best fit the type of actions.*

Examples of Hierarchical Models

- Despite drawbacks of the hierarchical paradigm, it has been deployed in various systems, e.g., *Nested Hierarchical Controller* and *NIST Realtime Control System*.

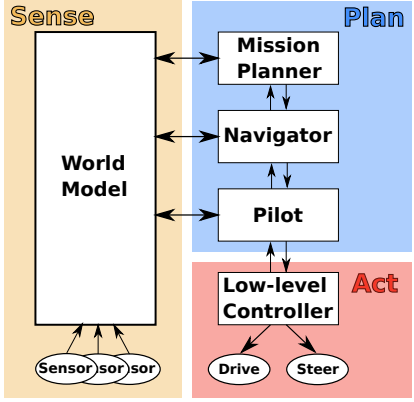
  It was used until 1980, when the focus was changed to the reactive paradigm.

- The development of hierarchical models further exhibited additional advancements such as a potential to address the **frame problem**.
- They also provide a way to organize the particular blocks of the control architecture.
- Finally, the hierarchical model represents an architecture that **supports evolution and learning systems** towards fully autonomous control.

Nested Hierarchical Controller

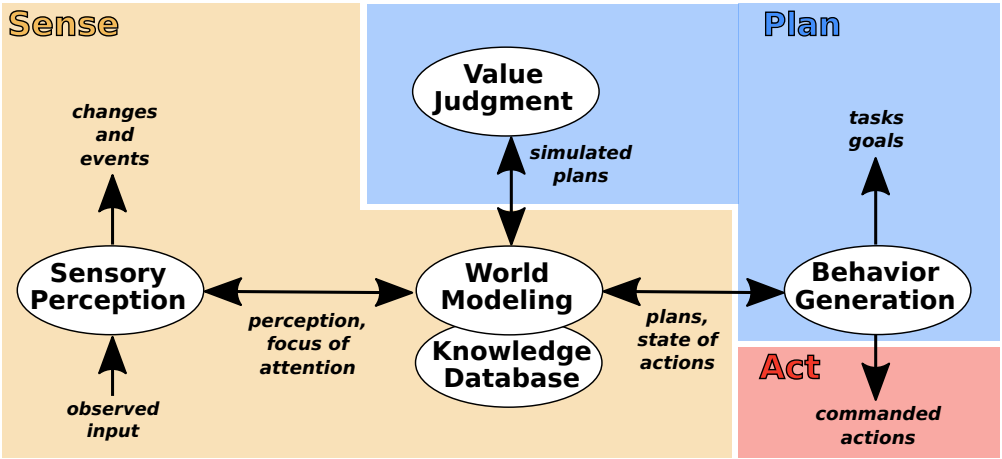
- Decomposition of the planner into three different subsystems: **Mission Planner**, **Navigation**, **Pilot**.
- **Navigation** is planning a path as a sequence of waypoints.
- **Pilot** generates an action to follow the path.

  It can response to sudden objects in the navigation course. The plan exists, and it is not necessary to perform complete planning.



Overview of the Real-time Control System (RCS)

- Key features are sensor preprocessing, plan simulator for evaluation, and behavior generator.



Hierarchical Paradigm – Summary

- Hierarchical paradigm represents **deliberative architecture** also called **sense-plan-act**.
- The robot control is decomposed into functional modules that are sequentially executed.

  The output of the sense module is the input of the plan module, etc.
- It has centralized representation and reasoning.
- May need extensive and computationally demanding reasoning.
- Encourage open loop execution of the generated plans.
- Several architectures have been proposed, e.g., using STRIP planner in Shakey, Nested Hierarchical Controller (NHC), NIST Real-time Control System (RCS).

  NIST – National Institute of Standards and Technology

Despite the drawbacks, hierarchical architectures tend to support the evolution of intelligence from semi-autonomous control to fully autonomous control.



Navlab Testbed 1986 – https://youtu.be/ntIczNQKfjQ

Navlab vehicles 1–5

Navlab (1996) uses 90% of autonomous steering from Washington DC to Los Angeles.

History Corner

- Where to? A history of autonomous vehicles.

  https://computerhistory.org/blog/where-to-a-history-of-autonomous-vehicles/

  - Stanford Artificial Intelligence Laboratory Cart, 1964-71.
  - Ernst Dickmanns' VaMoRs Mercedes van, Bundeswehr University Munich, 1986-2003.
  - Navlab 1 – Navlab 5, 1984–1990. https://www.cs.cmu.edu/afs/cs/usr/tjochem/www/nhaa/navlab5_details.html

    Driverless Car Technology Overview at Carnegie Mellon University – https://www.youtube.com/watch?v=2KMAAmkz9go
  - DARPA Grand Challenge – 2004 (no winner) and 2005 in Desert Southwest (6 h 53 min).
  - DARPA Urban Challenge 2007.

Navlab 1 (1986)

http://youtu.be/ntIczNQKfjQ

Navlab 5 (1997)

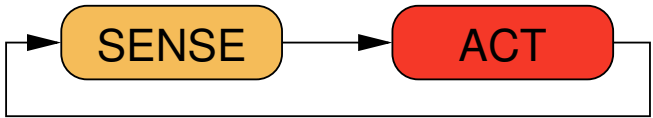
http://youtu.be/xkJVV1_418E

VaMoRs (1986–2003)

http://youtu.be/I39sxwYK1EE

Reactive Paradigm

- The **reactive paradigm** is a connection of sensing with acting.



- It is biologically inspired as humans and animals provide evidence of intelligent behavior in an **open world**, and thus it may be possible to overcome the **close world assumption**.
- Insects, fish, and other "simple" animals exhibit intelligent behavior without virtually no brain.
- There must be the same mechanism that avoids the **frame problem**.
- For further discussion, we need some terms to discuss the properties of "intelligence" of various entities.

Agent and Computational-Level Theory

- **Agent** is a self-contained and independent entity.
  - It can interact with the world to make changes and sense the world.
  - It has **self-awareness**.
- The reactive paradigm is influenced by Computational-Level Theories.

  D. Marr, a neurophysiologist who worked on computer vision techniques inspired by biological vision processes.

  - **Computational Level** – **What?** and **Why?**

    What is the goal of the computation, and why is it relevant?

  - **Algorithmic level** – **How?** *Focus on the process rather than the implementation.*

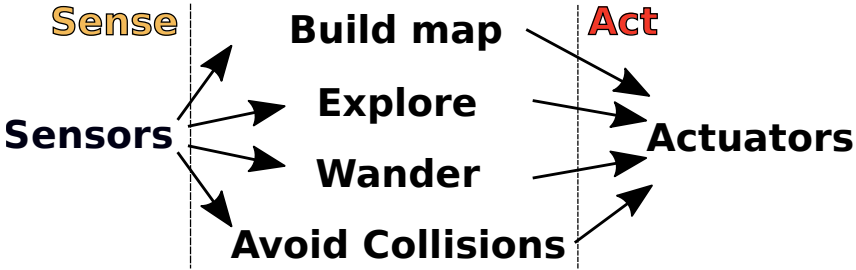
    How to implement the computational theory? What is the representation of input and output? What is the algorithm for the transformation of input to output?

  - **Physical level** – How to implement the process?

    How to physically realize the representation and algorithm?

Reactive Paradigm

- Reactive paradigm originates from dissatisfaction with the hierarchical paradigm (S-P-A), which is influenced by ethology.

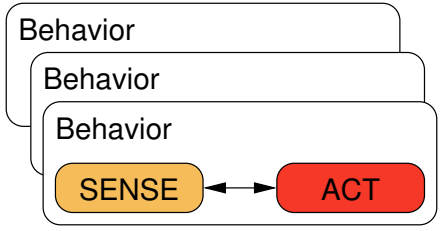


- Contrary to the S-P-A, which exhibits horizontal decomposition, the reactive paradigm (S-A) provides *vertical decomposition*.
  - Behaviors are layered, where lower layers are "survival" behaviors.
  - Upper layers may reuse the lower, inhibit them, or create parallel tracks of more advanced behaviors.

If an upper layer fails, the bottom layers would still operate.

Multiple, Concurrent Behaviors

- Strictly speaking, one behavior does not know what another behavior is doing or perceiving.



- Mechanisms for handling simultaneously active multiple behaviors are needed for complex reactive architectures.
- Two main representative methods have been proposed in the literature.
  - **Subsumption architecture** proposed by Rodney Brooks.
  - **Potential fields** methodology studied by Ronald Arkin, David Payton, et al.

Characteristics of Reactive Behaviors

1. Robots are **situated agents** operating in an ecological niche.
   - Robot has its intentions and goals; it changes the world by its actions, and what it senses influences its goals.
2. *Behaviors serve as the building blocks for robotic actions, and the overall behavior of the robot is* ***emergent****.*
3. *Only local, behavior-specific sensing is permitted* – usage of explicit abstract representation is avoided – **ego-centric** representation.

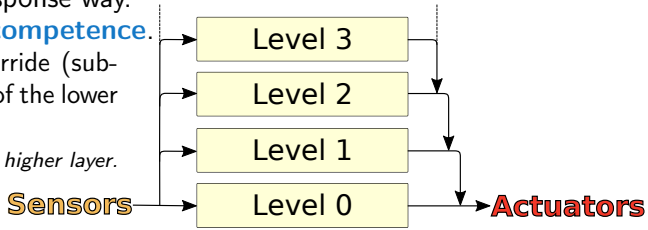
   E.g., robot-centric coordinates of an obstacle are relative and not in the world coordinates.
4. Reactive-based systems follow good software design principles – modularity of behaviors supports decomposition of a task into particular behaviors.
   - Behaviors can be tested independently.
   - Behaviors can be created from other (primitive) behaviors.
5. Reactive-based systems or behaviors are often biologically inspired.

   Under reactive paradigm, it is acceptable to mimic biological intelligence.

An Overview of Subsumption Architecture

- Subsumption architecture has been deployed in many robots that exhibit walk, collision avoidance, etc. without the "move-think-move-think" pauses of Shakey.
- Behaviors are released in a stimulus-response way.
- Modules are organized into **layers of competence**.
  1. Modules at the higher layer can override (subsume) the output from the behaviors of the lower layer.

     Winner-take-all – the winner is the higher layer.

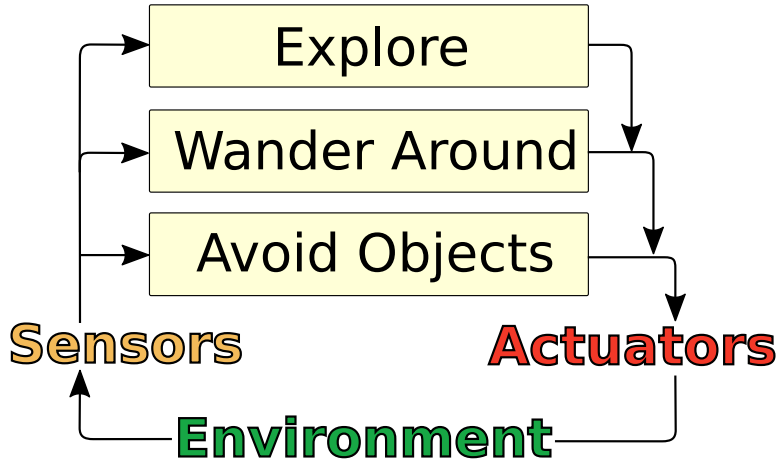


  2. Internal states are avoided.

     A good behavioral design minimizes the internal states that can be, e.g., used in releasing behavior.
  3. A task is accomplished by activating the appropriate layer that activates a lower layer and so on.
- In practice, the subsumption-based system is not easily taskable.

  It needs to be reprogrammed for a different task; however, it can serve well for the defined task.

An Example of Subsumption Architecture

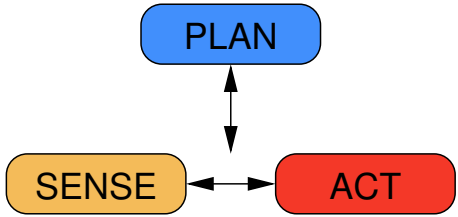


Further reading: R. Murphy, Introduction to AI Robotics.

Hybrid Paradigm

- The main drawback of reactive-based architectures is a lack of planning and reasoning about the world.
  - An example is a robot that cannot plan an optimal trajectory.
- Hybrid architecture combines the hierarchical (deliberative) paradigm with the reactive paradigm.

Beginning of the 1990's



- Hybrid architecture can be described as **Plan**, then **Sense-Act**.
  - Planning covers a relatively long time horizon, and it uses a global world model.
  - Sense-Act covers the reactive (real-time) part of the control.

Characteristics of Reactive Paradigm in Hybrid Paradigm

- **Hybrid paradigm** is an extension of the **Reactive paradigm**.
- The term behavior in the hybrid paradigm includes reflexive, innate, and learned behaviors.

  In the reactive paradigm, it connotes purely reflexive behaviors.
- Behaviors are also sequenced over time, and more complex emergent behaviors can occur.
- **Behavioural management** – planning which behavior to use requires information outside the particular model (a global knowledge).

  Reactive behavior works without any outside knowledge.
- **Performance monitor** evaluates if the robot is making progress toward its goal.

  For example, whether the robot is moving or stuck.
  - In order to monitor the progress, the program has to know the behavior the robot is trying to accomplish.

Components of Hybrid Deliberative/Reactive Paradigm

- **Sequencer** – generates a set of behaviors to accomplish a subtask.
- **Resource Manager** – allocates resources to behaviors, which can include a selection of suitable sensors. *In reactive architectures, resources for behaviors are usually hardcoded.*
- **Cartographer** – creates, stores, and maintains a map or spatial information, a global world model, and knowledge representation. *It can be a map but not necessarily.*
- **Mission Planner** – interacts with the operator and transforms the commands into the robot term.
  - Construct a mission plan. For a mobile robot, it can consist of navigation to some place where further action is taken.
- **Performance Monitoring and Problem Solving** – it is a sort of **self-awareness** allowing the robot to monitor its progress.

Existing Hybrid Architectures

- Managerial architectures use agents for high-level planning at the top; then there are agents for plan refinement to the reactive behaviors at the lowest level.

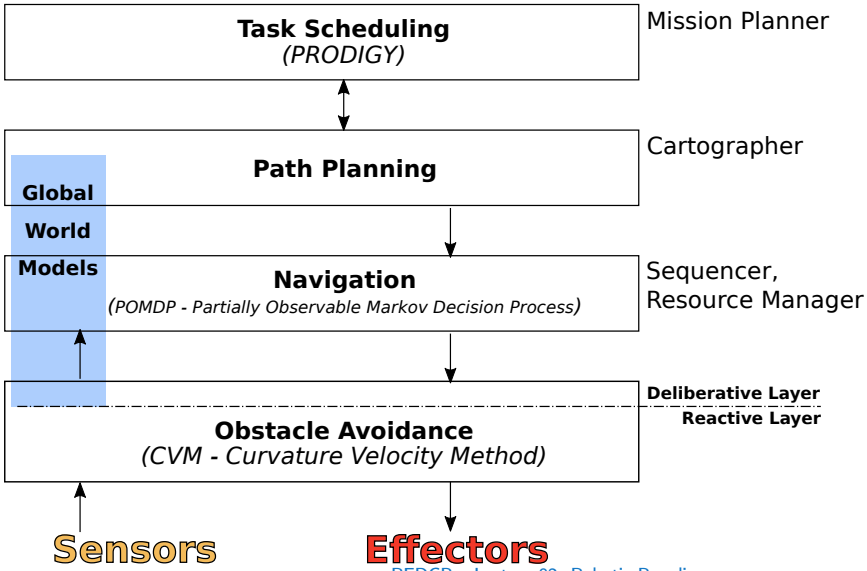
  E.g., Autonomous Robot Architecture, and Sensor Fusion Effects.

- State-Hierarchy architectures organize activity by the scope of the time knowledge

  E.g., 3-Tiered architectures.

- Model-Oriented architectures concentrate on symbolic manipulation around the global world. *E.g., Saphira.*
- **Task Control Architecture** (TCA) – layered architecture:
  - Sequencer Agent, Resource Manager – Navigation Layer;
  - Cartographer – Path-Planning Layer;
  - Mission Planner – Task Scheduling Layer;
  - Performance Monitoring Agent – Navigation, Path-Planning, Task-Scheduling;
  - Emergent Behavior – Filtering.

Task Architecture

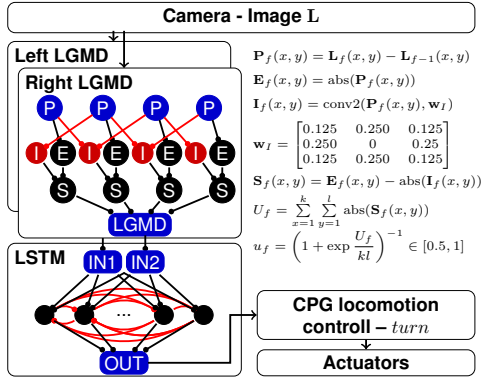


Example of Reactive Collision Avoidance

- Biologically inspired reactive architecture with vision sensor and CPG.

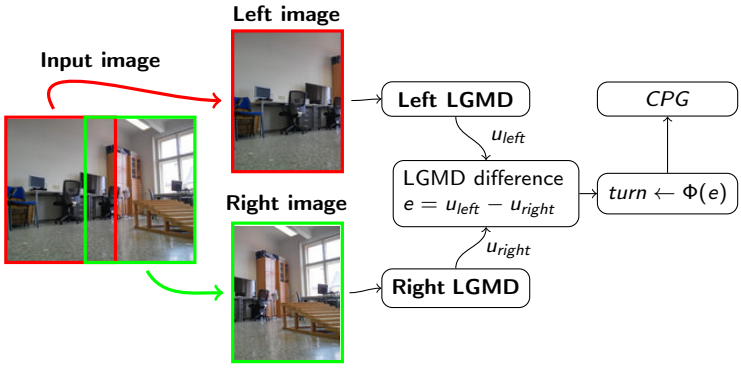
  Notice all are hardwired into the program, and the robot goes "just" ahead with avoiding intercepting obstacles.

  - CPG-based locomotion control can be parametrized to steer the robot motion to the left or right.
  - **Avoiding collisions** with obstacles and intercepting objects is based on the visual perception inspired by the Lobula Giant Movement Detector (LGMD), which is a neural network detecting approaching objects.



Čížek, Milička, Faigl (IJCNN 2017)

LGMD-based Collision Avoidance – Control Rule

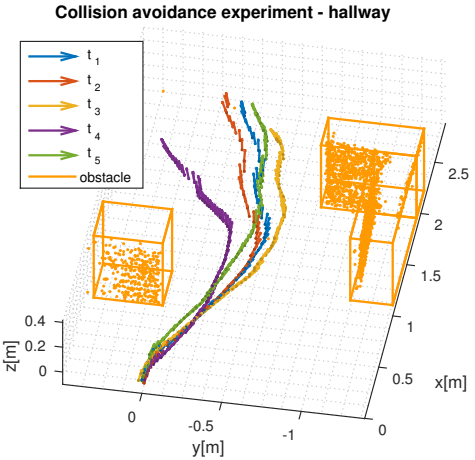


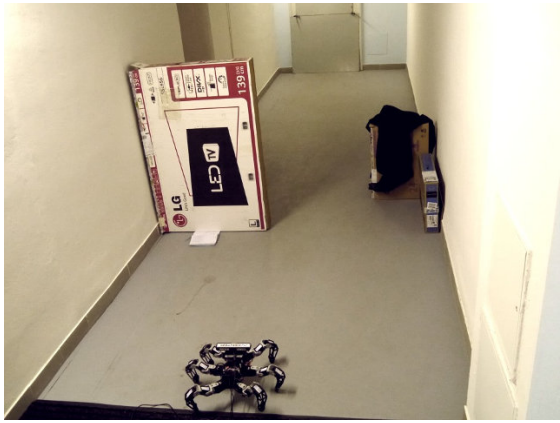
A mapping function: Φ from the output of the LGMD vision system to the *turn* parameter of the CPG

$$\Phi(e) = \begin{cases} 100/e & \text{for } \text{abs}(e) \geq 0.2 \\ 10000 \cdot \text{sgn}(e) & \text{for } \text{abs}(e) < 0.2 \end{cases} .$$

Čížek, Milička, Faigl (IJCNN 2017)

Example of LGMD-based Collision Avoidance



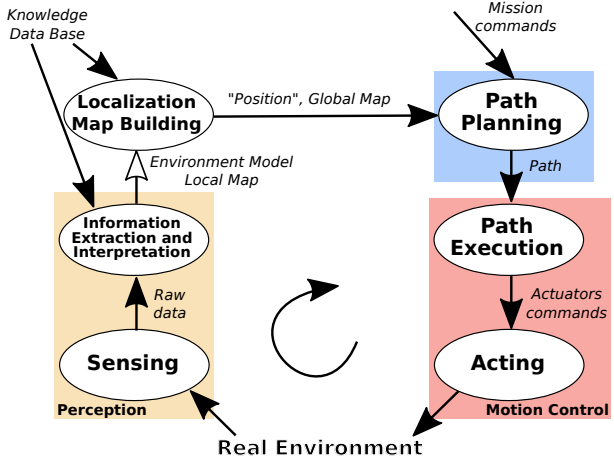


- LGMD output together with the proposed mapping function provide a smooth motion of the robot.

Čížek, Faigl (Bioinspiration & Biomimetics, 2019)

A Control Schema for a Mobile Robot

- A general control schema for a mobile robot consists of **Perception Module**, **Localization and Mapping Module**, **Path Planning Module**, and **Motion Control Module**.



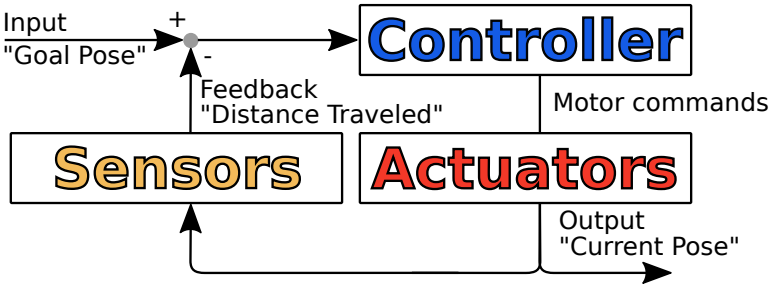
Motion Control

- An important part of navigation is the execution of the planned path.
- Motion control module is responsible for the path realization.
  - **Position control** aims to navigate the robot to the desired location.
  - **Path-Following** is a controller that aims to navigate the robot along the given path.
  - **Trajectory-Tracking** differs from the path-following in that the controller forces the robot to reach and follow a time parametrized reference (path).

    E.g., a geometric path with an associated timing law.
- The controller can be realized as one of two types:
  - **Feedback controller**;
  - **Feedforward controller**.

FeedBack Controller

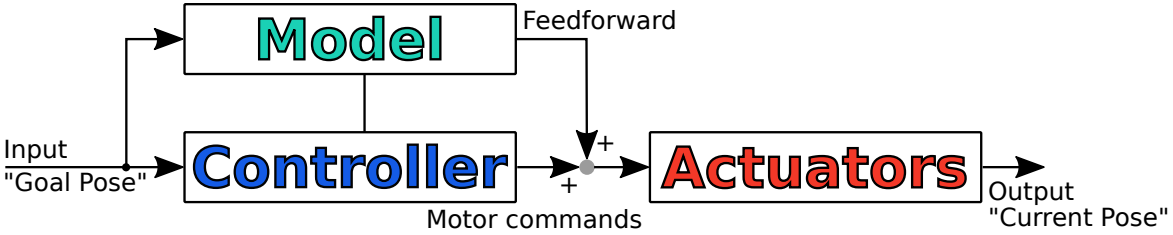
- The difference between the goal pose and the distance traveled so far is the error used to control the motors.
- The controller commands the motors (actuators), which change the real robot pose.
- Sensors, such as encoders for a wheeled robot, provide information about the traveled distance.



Notice, the robot may stuck, but it is not necessarily detected by the encoders.

Feed-Forward Controller

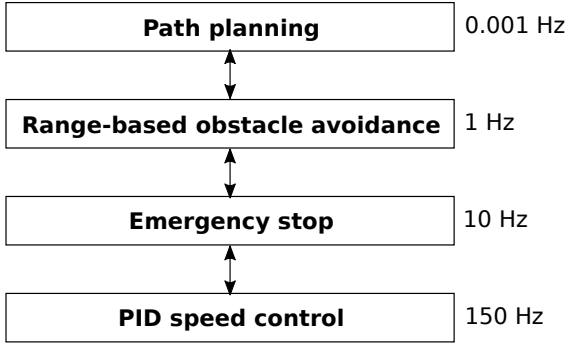
- In the feed-forward controller, there is no feedback from the real-world execution of the performed actions.
- Instead of that, a model of the robot is employed in the calculation of the expected effect of the performed action.



In this case, we fully rely on the assumption that the actuators will be performed as expected.

Temporal Decomposition of Control Layers

- The robot control architecture typically consists of several modules (behaviors) that may run at different frequencies.
- Low-level control is usually the fastest, while path planning is slower as the robot needs some time to reach the desired location.
- An example of possible control frequencies of different control layers.



Adapted from Introduction to Autonomous Mobile Robots, R. Siegwart et al.

Summary of the Lecture

Topics Discussed

- Robotic Paradigms:
  1. Hiearchical paradigm;
  2. Reactive paradigm;
  3. Hybrid Hiearchical/Reactive paradigm.
- Example of Reactive architecture – collision avoidance.
- Robot Control.

- Next: Path and Motion Planning.