EPFL

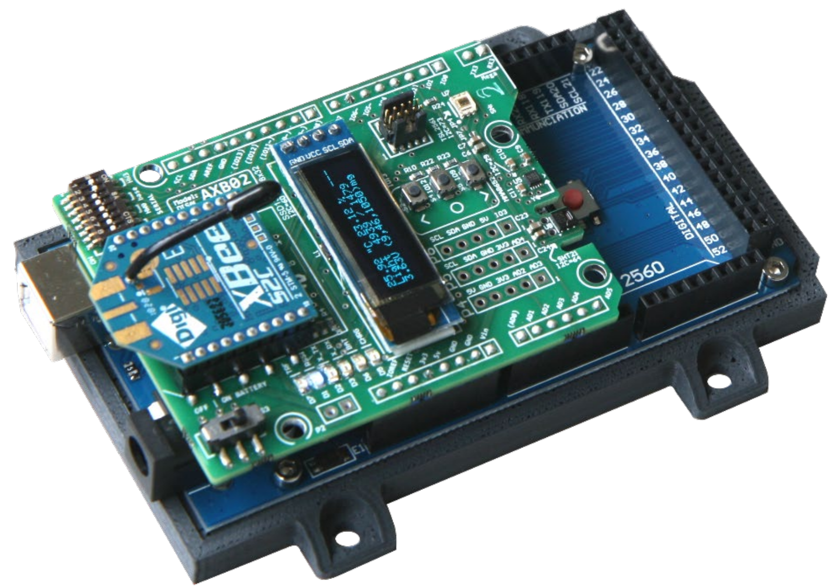
Disal

Signals, Instruments, and Systems – W5

Introduction to Programmable Instruments and Embedded Systems

Outline

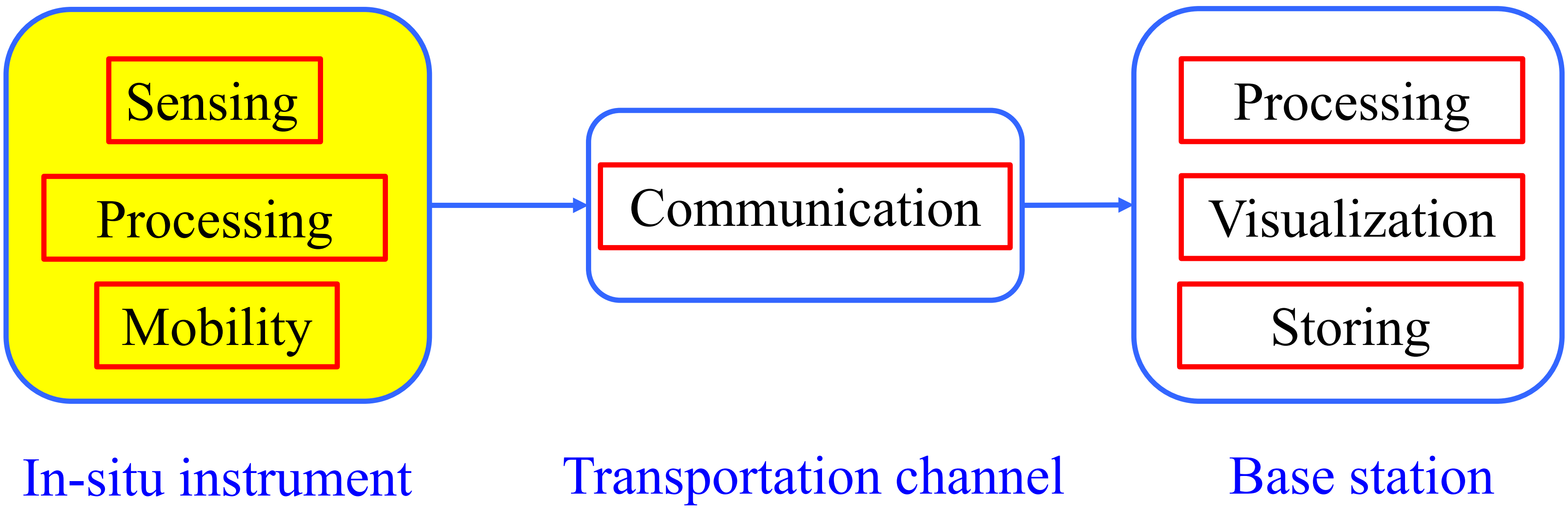
- Motivation
- Embedded system terminology, key concepts, and examples
- Perception and sensors
- Computation and control
- The e-puck as example of embedded system



Motivation

- This course is about Signals, Instruments, and Systems
- We have seen examples of signals and systems and their synthesis/analysis; it is time to go towards programmable instruments
- From next week you will restart programming in C
- In a regular edition, this is when we would introduce embedded C programming and real hardware (DISAL Arduino node); given the pandemic restrictions it is more useful to make a liaison towards the high-fidelity robotic simulator Webots

Motivation from Week 1 Lecture



Highlighted block are those mainly leveraging the content of this lecture.

Embedded Systems

What is an Embedded System?

From Wikipedia:

An **embedded system** is a special-purpose computer system designed to perform one or a few dedicated functions often with real-time computing constraints. It is usually *embedded* as part of a complete device including hardware and mechanical parts. Examples of properties of typically embedded computers when compared with general-purpose counterparts are low power consumption, small size, rugged operating ranges, and low per-unit cost.

What is Challenging in Designing Embedded Systems?

- Computation is subject to physical and resource constraints such as timing, deadlines, memory restrictions, and power consumption requirements.
- The traditional abstraction of separating software from the hardware is more difficult. Hardware and software are integrally intertwined.
- But: hardware components are becoming more and more flexible, cheap, small, and standardized. The design complexity is shifting to software!
- Your role as Environmental/Civil Engineers: get enough background to contribute to the software side with your domain knowledge and collaborate with electrical/computer/mechanical/mechatronic engineers.

Perception - Sensors

- Proprioceptive ("body") vs. exteroceptive ("environment")
  - *Ex. proprioceptive*: motor speed/robot arm joint angle, battery voltage, acceleration
  - *Ex. exteroceptive:* distance measurement, light intensity, sound amplitude, temperature, wind speed
- Passive ("measure ambient energy") vs. active ("emit energy in the environment and measure the environmental reaction")
  - *Ex. passive*: temperature probes, microphones, cameras
  - *Ex. active*: laser range finder (LIDAR), IR proximity sensors, ultrasound sonars, ultrasound anemometers

[Adapted from *Introduction to Autonomous Mobile Robots*, Siegwart R. and Nourbakhsh I. R.]

Computation

- Usually microcontroller-based
- Microcontrollers are all-in-one computer chips. They contain a processing core, memory, and integrated peripherals (e.g., ADC, motor control PWM generator, bus controller).
- Capable of Analog-to-Digital Conversion (e.g., ADC) and Digital-to-Analog Conversion (e.g., PWM generator)

Communication

- Different physical channels: wired (e.g., RS232, CAN, USB) and wireless (e.g., radio, infrared, ultrasound, sound)
- Internal or external to the device: buses connecting different components; external (e.g., node-to-node or node-to-basestation)
- Asymmetric (one way) or symmetric (bidirectional) link
- Direct (explicit) or indirect (implicit): *direct* implies dedicated hardware and software components for intentional, targeted information sharing; *indirect*, implies anonymous, broadcasting forms (e.g., visual signs)

Examples of Embedded Systems

Consumer Market Devices

Weather station

Digital Watch

Digital camera

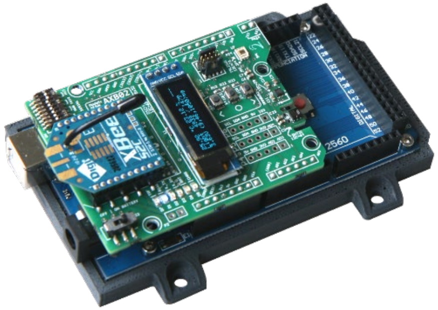
Digital video camera

Niche Market – Scientific Equipment Commercially Available

Sensorscope station

e-puck robot

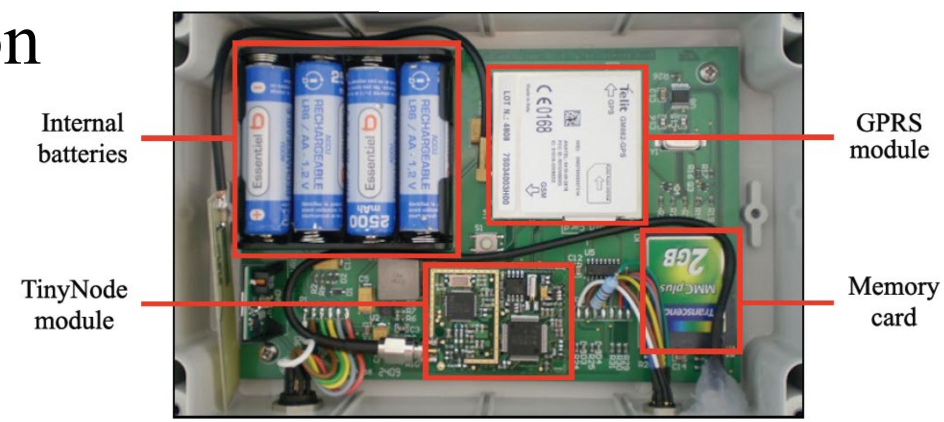
DISAL
Arduino Node



Handheld Airborne Mapping System

The Example of *Sensorscope* Stations

- What is measured:
  - temperature
  - humidity
  - precipitation
  - wind speed/direction
  - solar radiation
  - soil moisture



Pictures: courtesy of SwissExperiment

Perception and Sensors

Classification of Typical Sensors

General classification (typical use)	Sensor Sensor System	PC or EC	A or P
Tactile sensors (detection of physical contact or closeness; security switches)	Contact switches, bumpers	EC	P
	Optical barriers	EC	A
	Noncontact proximity sensors	EC	A
Wheel/motor sensors (wheel/motor speed and position)	Brush encoders	PC	P
	Potentiometers	PC	P
	Synchros, resolvers	PC	A
	Optical encoders	PC	A
	Magnetic encoders	PC	A
	Inductive encoders	PC	A
	Capacitive encoders	PC	A
Heading sensors (orientation of the robot in relation to a fixed reference frame)	Compass	EC	P
	Gyroscopes	PC	P
	Inclinometers	EC	A/P

A, active; P, passive; P/A, passive/active; PC, proprioceptive; EC, exteroceptive.

[From *Introduction to Autonomous Mobile Robots*, Siegwart R. and Nourbakhsh I. R.]

Classification of Typical Sensors

General classification (typical use)	Sensor Sensor System	PC or EC	A or P
Ground-based beacons (localization in a fixed reference frame)	GPS Active optical or RF beacons Active ultrasonic beacons Reflective beacons	EC EC EC EC	A A A A
Active ranging (reflectivity, time-of-flight, and geometric triangulation)	Reflectivity sensors Ultrasonic sensor Laser rangefinder Optical triangulation (1D) Structured light (2D)	EC EC EC EC EC	A A A A A
Motion/speed sensors (speed relative to fixed or moving objects)	Doppler radar Doppler sound	EC EC	A A
Vision-based sensors (visual ranging, whole-image analysis, segmentation, object recognition)	CCD/CMOS camera(s) Visual ranging packages Object tracking packages	EC	P

[From *Introduction to Autonomous Mobile Robots*, Siegwart R. and Nourbakhsh I. R.]

General Sensor Performance

– Range
  - Upper limit
– Dynamic range
  - ratio between lower and upper limits, usually in decibels (dB for power and amplitude)
  - e.g. voltage measurement from 1 mV to 20 V

$$20 \cdot \log\left[\frac{20}{0.001}\right] = 86dB$$

Note: see also W4 lecture on magnitude in Bode plots

  - e.g. power measurement from 1 mW to 20 W

$$10 \cdot \log\left[\frac{20}{0.001}\right] = 43dB \qquad P = U \cdot I = \frac{1}{R}U^2$$

[Adapted from *Introduction to Autonomous Mobile Robots*, Siegwart R. and Nourbakhsh I. R.]

General Sensor Performance

– Resolution
  - minimum difference between two values
  - usually: lower limit of dynamic range = resolution
  - for digital sensors it is usually the A/D resolution.
    - e.g. 5V / 255 (8 bit)

– Linearity
  - variation of output signal as function of the input signal
  - linearity is less important when signal is treated with a computer

$$x \to f(x)$$
$$y \to f(y)$$

$$\alpha \cdot x + \beta \cdot y \to f(\alpha \cdot x + \beta \cdot y) \stackrel{?}{=} \alpha \cdot f(x) + \beta \cdot f(y)$$

[From *Introduction to Autonomous Mobile Robots*, Siegwart R. and Nourbakhsh I. R.]

General Sensor Performance

– Bandwidth or Frequency
  - the speed with which a sensor can provide a stream of readings
  - usually there is an upper limit depending on the sensor and the sampling rate
  - lower limit is also possible, e.g. acceleration sensor
  - frequency response (see W4, a sensor is another example of system): phase and amplitude of the transduced signal might be influenced

[Adapted from *Introduction to Autonomous Mobile Robots*, Siegwart R. and Nourbakhsh I. R.]

In Situ Sensor Performance

Characteristics that are especially relevant for real world environments

- Sensitivity
  - ratio of output change to input change
  - however, in real world environment, the sensor has very often high sensitivity to other environmental changes, e.g. illumination
- Cross-sensitivity (and cross-talk)
  - sensitivity to other environmental parameters
  - influence of other active sensors
- Error / Accuracy
  - difference between the sensor's output and the true value

error

$$\left(accuracy = 1 - \frac{|m - v|}{v} \right)$$

m = *measured value*

v = *true value*

[Adapted from *Introduction to Autonomous Mobile Robots*, Siegwart R. and Nourbakhsh I. R.]

In Situ Sensor Performance

Characteristics that are especially relevant for real world environments

- Systematic error -> deterministic errors
  - caused by factors that can (in theory) be modeled -> prediction
  - e.g., calibration of a laser sensor or camera optics
- Random error -> non-deterministic
  - no deterministic prediction possible
  - however, they can be described probabilistically
  - e.g. Gaussian noise on a distance sensor, black level noise of camera
- Precision (different from accuracy!)
  - *reproducibility* of sensor results

$$precision = \frac{range}{\sigma}$$

σ = standard dev of the sensor noise

[From *Introduction to Autonomous Mobile Robots*, Siegwart R. and Nourbakhsh I. R.]

Computation and Control

Open-Loop vs. Closed-Loop Control

- **Open-loop example**: An heating system, programmed to turn on at set times: it does not measure temperature as a form of feedback. Even if the sun is warming the room, the heating system would activate on schedule, wasting energy.

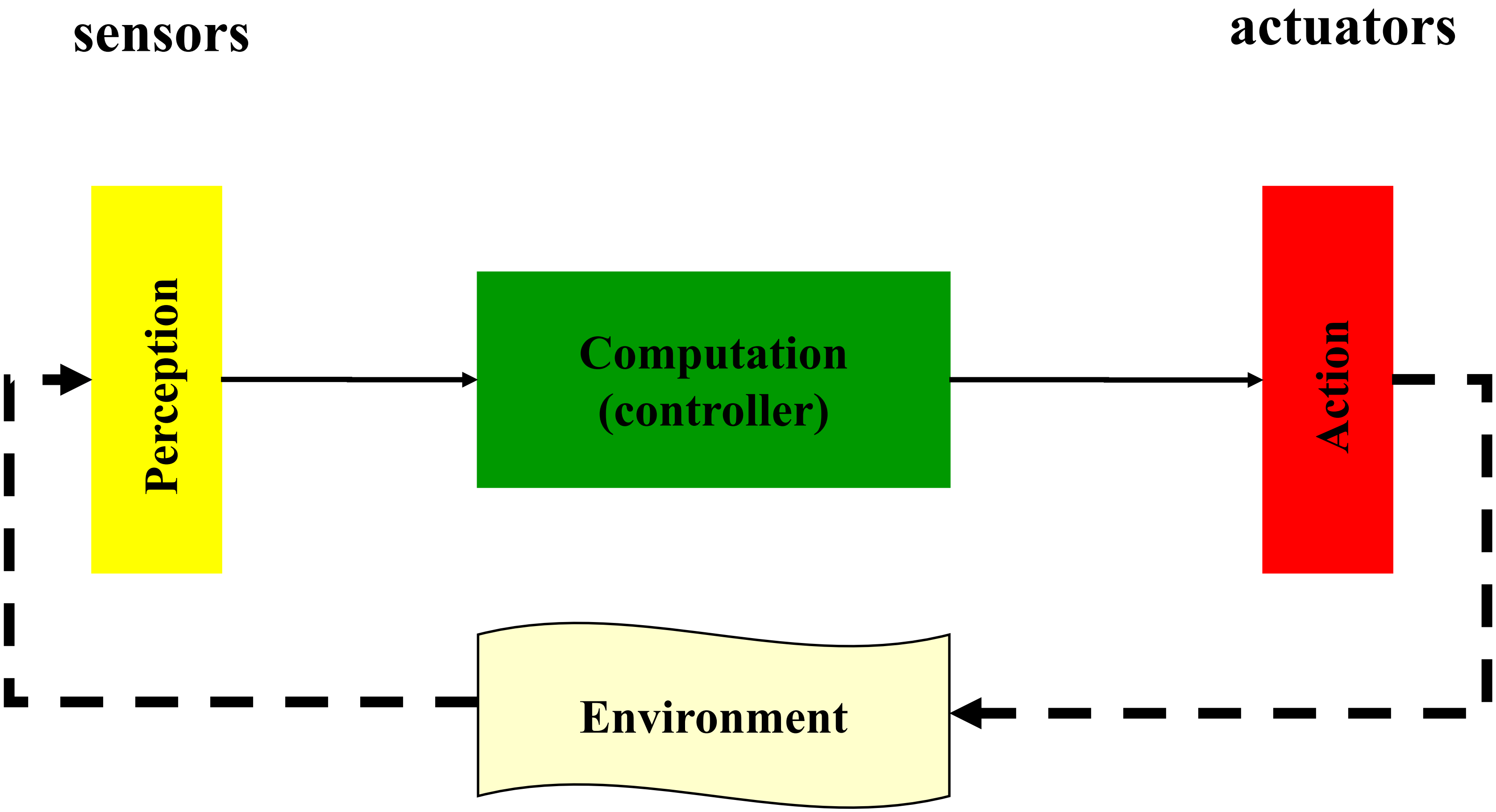
- **Closed-loop example**: An heating system which adjust the heating time as a function of the measured temperature. If the sun is warming the room, the heating system will be activated less often than in a rainy day.

What is a Controller?

- In this course (in embedded systems), a **controller** is a piece of software which monitors and affects the operational conditions of a given dynamical system consisting of the device hardware and the environment.

- Example, the heating system of a room (closed-loop):
  - Sensing: temperature probe
  - Controller: algorithm running on a programmable thermostat (measure temperature and control the heater)
  - Actuation: heater
  - Dynamical system: room + programmable thermostat (e.g., microcontroller-based)

Perception-to-Action Loop



Note: real-time aspect emphasized!

The e-puck Miniature Robot as Example of Embedded System

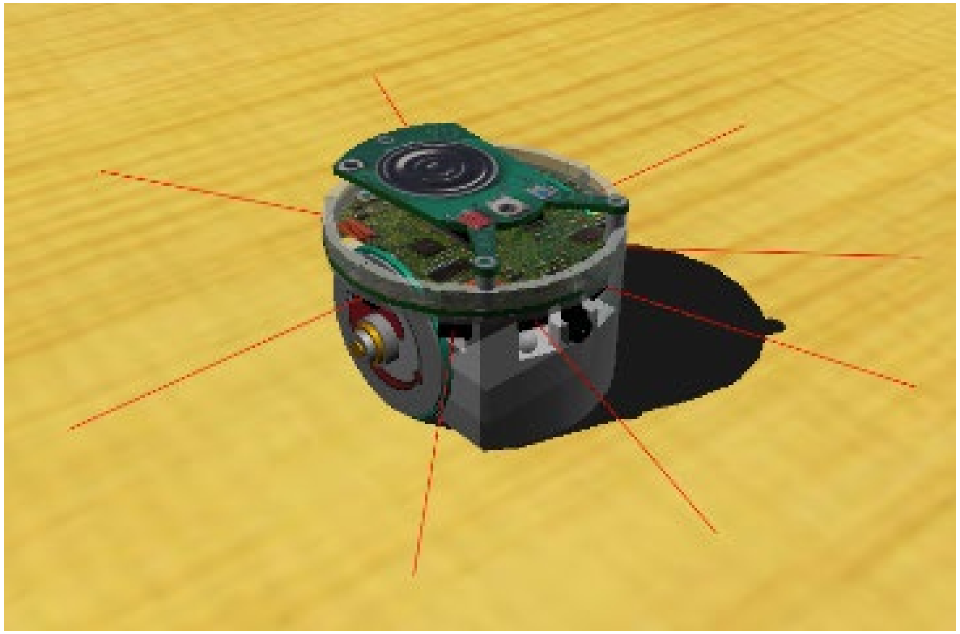
The e-puck Mobile Robot

Main features

- Cylindrical, Ø 70mm
- dsPIC processor
- Two stepper motors
- Ring of LEDs
- Many sensors:
  - ✓ Camera
  - ✓ Sound
  - ✓ IR proximity
  - ✓ 3D accelerometer
- Li-ion accumulator
- Bluetooth wireless communication
- Open hardware (and software)

http://www.e-puck.org/

Simulated and Real e-puck



Simulated e-puck (Webots)
- sensor- and actuator-based
- noise, nonlinearities of S&A reproduced
- kinematic (e.g., speed, position) and dynamic (e.g., mass, forces, friction)

Real e-puck

Conclusion

Take Home Messages

- Embedded system: specific purpose, equipped for interfacing discrete/digital and continuous/analog world, microcontroller-based design, often real-time constraints
- Main modules of an embedded system: perception, computation, communication, sometimes actuation
- Several examples of embedded systems in our daily life and for research/education purposes (e.g., Arduino, e-puck, Sensorscope)
- Some key concepts in perception and control
  - Proprioceptive/exteroceptive sensors, active/passive sensors,
  - Open- and closed-loop control
- The e-puck as example of embedded system in reality and simulation

Additional Literature – Week 5

Pointers:

- Permasense https://www.permasense.ch
- GITEWS – the German Indonesian Tsunami Early Warning System https://www.gitews.de
- Sensorscope https://www.sensorscope.ch

Books

- Siegwart R., Nourbakhsh I. R., and D. Scaramuzza, “Introduction to Autonomous Mobile Robots”, Second edition, MIT Press, 2011.
- Everett, H. R., “Sensors for Mobile Robots, Theory and Application”, A. K. Peters, Ltd., 1995.