EPFL

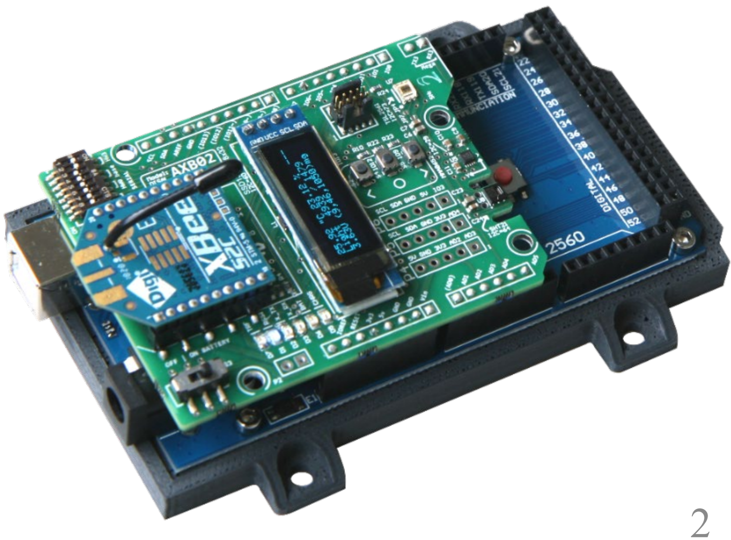
Disal

Signals, Instruments, and Systems – W6

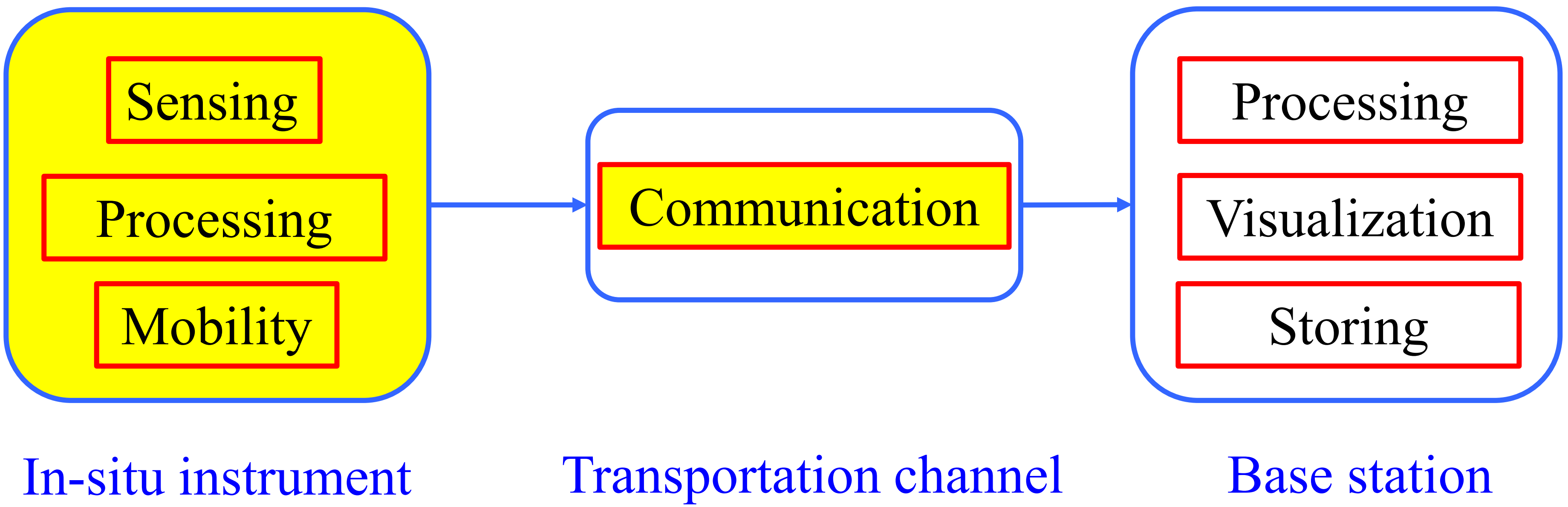
Introduction to Embedded Systems – Terminology, Perception, and Power

Outline

- Embedded systems
  - – Motivation
  - – Terminology, key concepts, blocks, and examples
  - – Perception and sensors
- Embedded systems used in the course
- Power in embedded systems
  - Field instruments as motivation
  - Power consumption
  - Power generation
  - Power storage



Motivation from Week 1 Lecture



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

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 field instruments
- From this week you will restart programming in C and Python (and keep using Matlab)

Embedded Systems

What is an Embedded System?

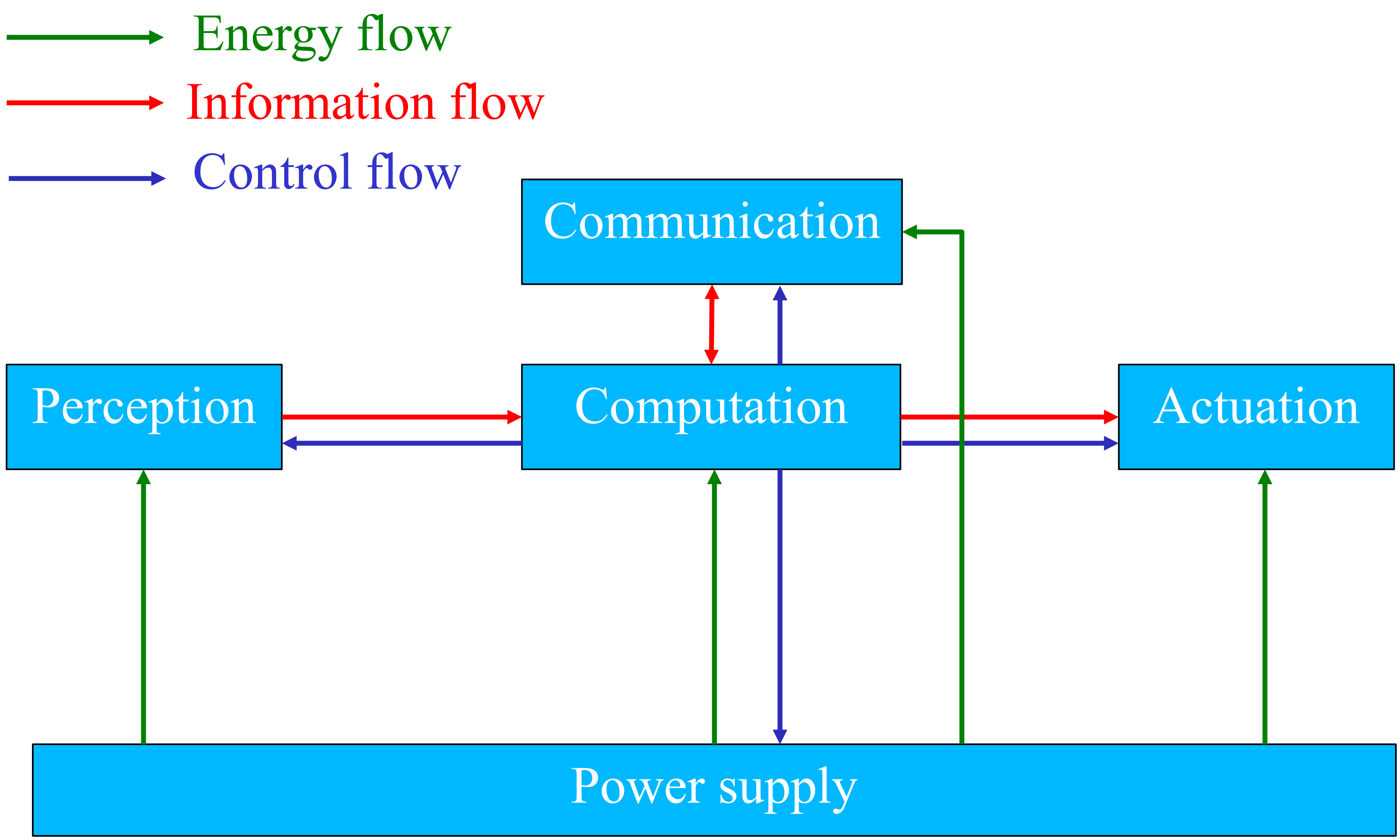
From Wikipedia:

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 Engineers: get enough background to contribute to the software side with your domain knowledge and collaborate with electrical, computer, mechanical, mechatronic engineers for the next generation of environmental field instruments.

Block Schema of an Embedded System



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)

Actuation - Actuators

- Actuator examples: motors, heaters, pumps, valves, LEDs, displays
- Motors not necessarily associated to self-locomotion such as those mechanically anchored to wheels, propellers, etc.
- Often high power consumption

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

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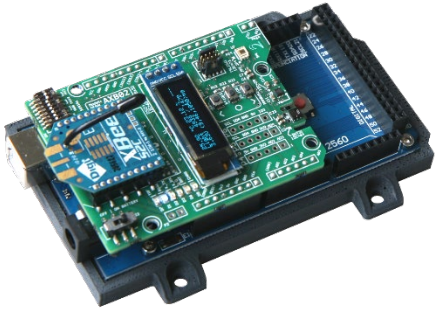
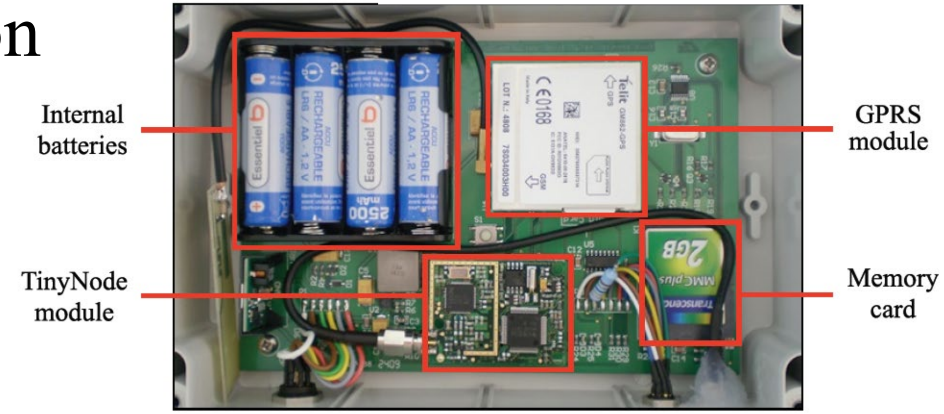
Arduino Node



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 root-power measurements, i.e. 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, s. 42

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

$$10 \cdot \log\left[\frac{20}{0.001}\right] = 43dB$$

Rem: $P = U \cdot I = \frac{1}{R} U^2$

[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; relevant also for frequency response (see LTI systems, W4/W5)
  - nonlinearities can be compensated/inverted digitally

$$x \rightarrow f(x)$$
$$y \rightarrow f(y)$$

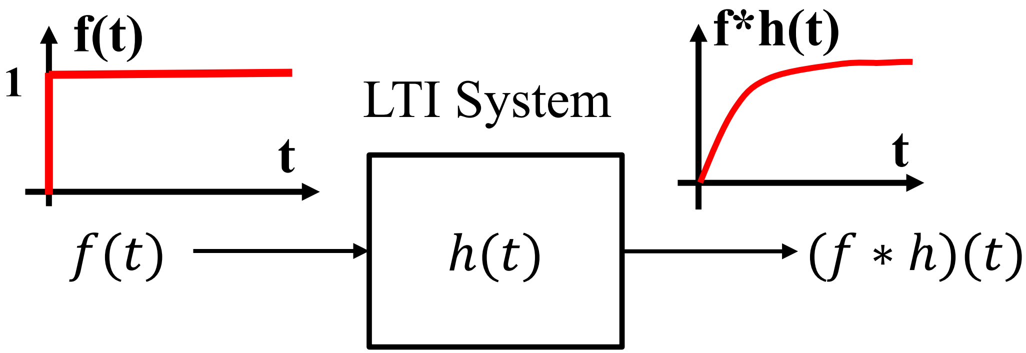
$$\alpha \cdot x + \beta \cdot y \rightarrow f(\alpha \cdot x + \beta \cdot y) \overset{?}{=} \alpha \cdot f(x) + \beta \cdot f(y)$$

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

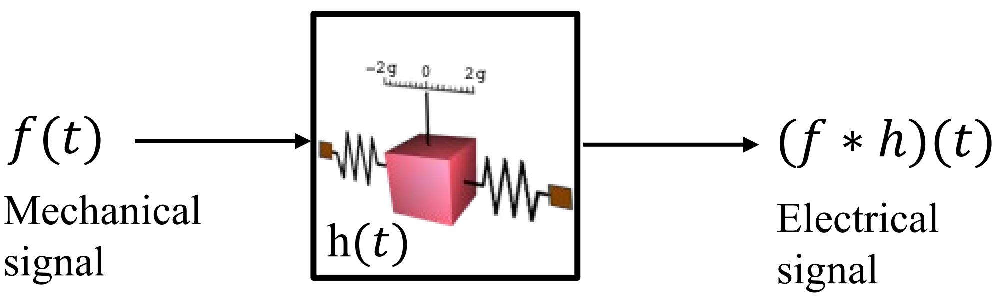
General Sensor Performance

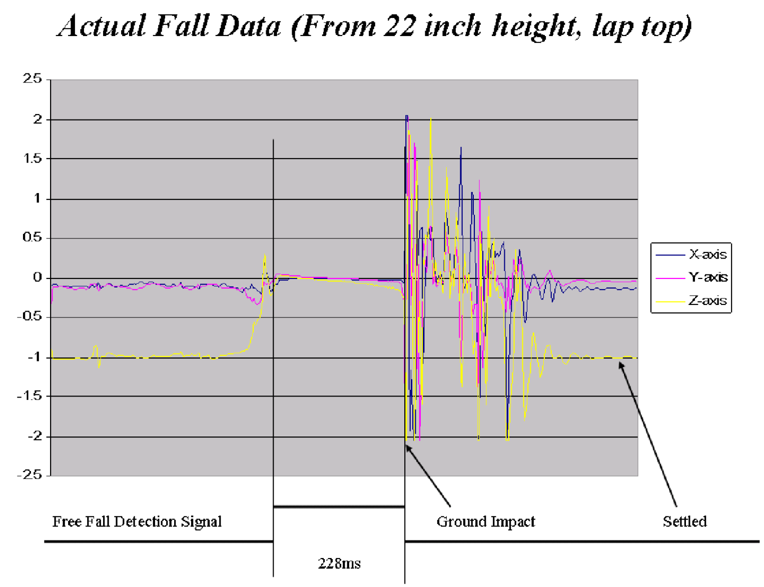
– Bandwidth or Frequency Response
  - the speed with which a sensor can provide a stream of readings
  - usually there is an upper limit depending on the sensor and the sampling rate
  - lower limit is also possible, e.g. acceleration sensor
  - frequency response: phase and amplitude of the transduced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

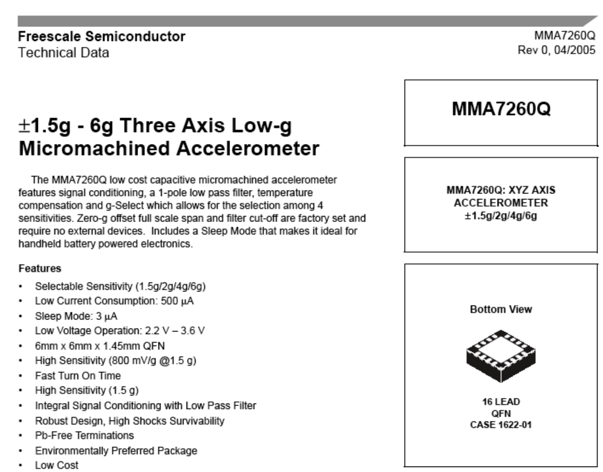
Sensor as a (LTI) System



Example: accelerometer







Freescale Semiconductor
Technical Data

MMA7260Q
Rev 0, 04/2005

MMA7260Q

±1.5g - 6g Three Axis Low-g Micromachined Accelerometer

The MMA7260Q low cost capacitive micromachined accelerometer features signal conditioning, a 1-pole low pass filter, temperature compensation and g-Select which allows for the selection among 4 sensitivities. Zero-g offset full scale span and filter cut-off are factory set and require no external devices. Includes a Sleep Mode that makes it ideal for handheld battery powered electronics.

MMA7260Q: XYZ AXIS ACCELEROMETER ±1.5g/2g/4g/6g

Features

- Selectable Sensitivity (1.5g/2g/4g/6g)
- Low Current Consumption: 500 µA
- Sleep Mode: 3 µA
- Low Voltage Operation: 2.2 V – 3.6 V
- 6mm x 6mm x 1.45mm QFN
- High Sensitivity (800 mV/g @1.5 g)
- Fast Turn On Time
- High Sensitivity (1.5 g)
- Integral Signal Conditioning with Low Pass Filter
- Robust Design, High Shocks Survivability
- Pb-Free Terminations
- Environmentally Preferred Package
- Low Cost

Bottom View

16 LEAD
QFN
CASE 1622-01

From data sheet of MMA7260Q

Low-pass filter

Bandwidth Response					
XY	f_{-3dB}	—	350	—	Hz
Z	f_{-3dB}	—	150	—	Hz

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 errors
  - 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

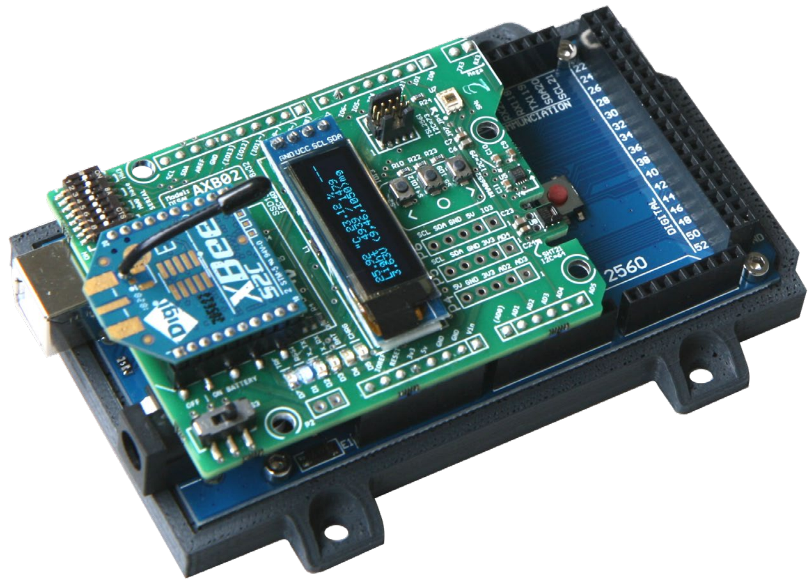
$$precision = \frac{range}{\sigma}$$

σ = standard dev of the sensor noise

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

Educational Embedded System used in the Course

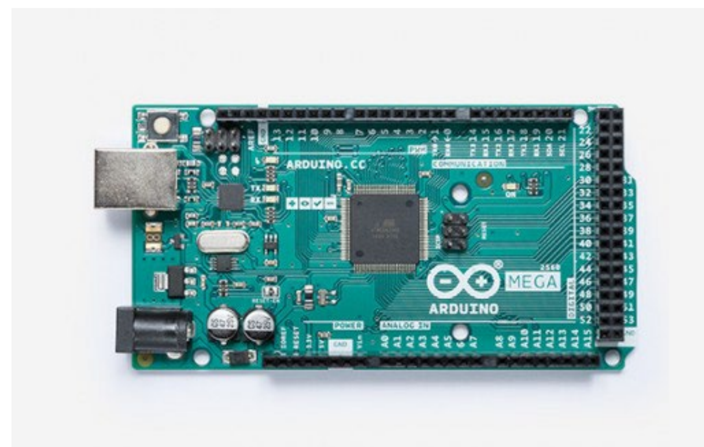
DISAL Arduino Xbee Node



- Computation: Arduino Mega 2560 board (ATMega 2560 microcontroller)
- Communication: Zigbee-complaint transceiver (Xbee)
- Actuation: on-board mini-display
- Perception:
  - Light sensor (TSL2561-T, ams)
  - Humidity and temperature sensor (SHT20, Sensirion)
  - 3D accelerometer (MMA8652, NXP)
- Power: 14 hours autonomy fully on (70 mA on 1000 mAh Li-Po battery)
- Can be programmed in C leveraging Arduino libraries

Arduino Mega 2560 Board

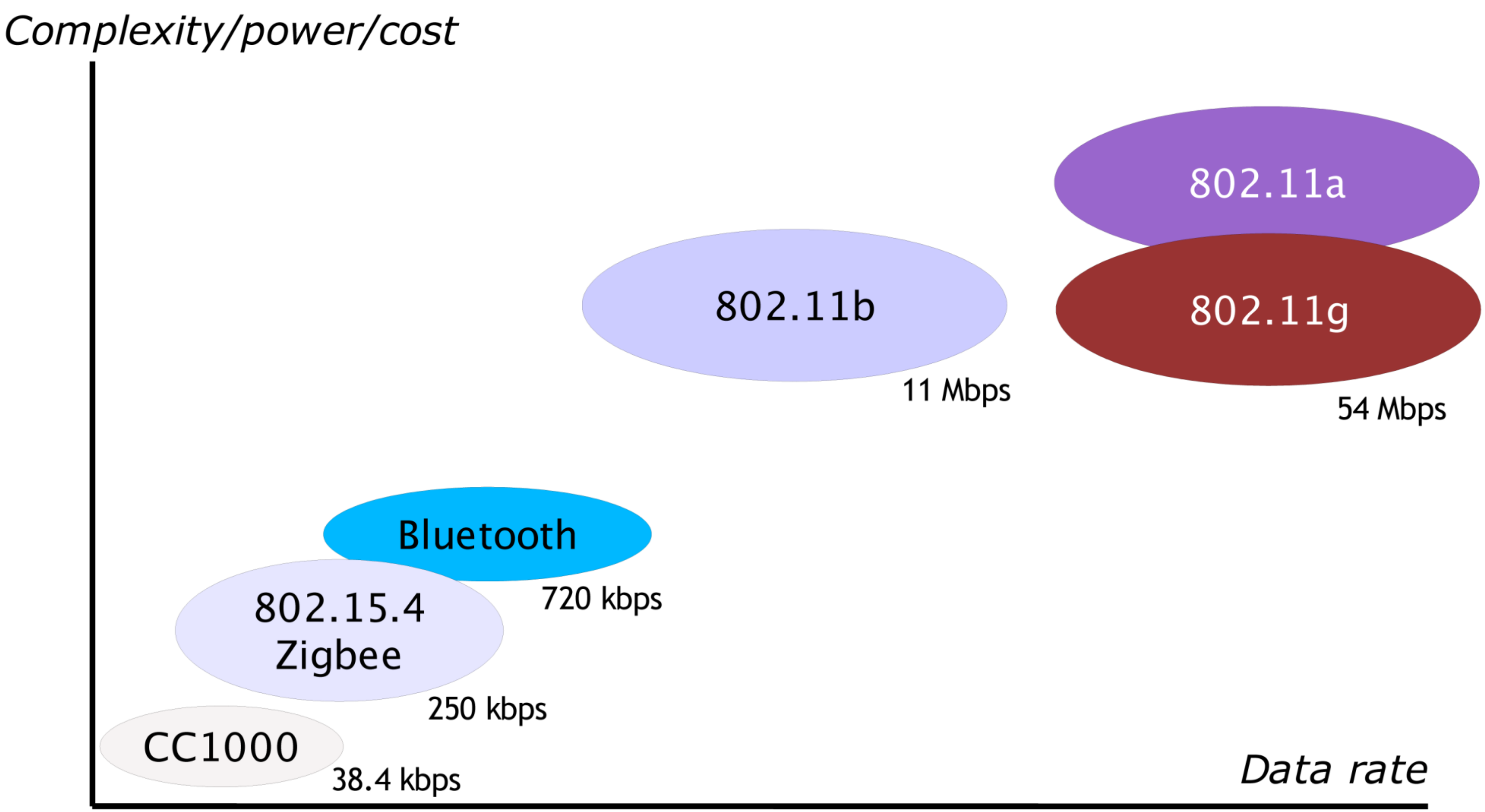
- 8-bit microcontroller
- 16 MHz clock, up to 16 MIPS
- 256 kB Flash memory (code)
- 8 kB SRAM (data)
- 16 analog inputs, 54 digital I/O
- 4 UARTs, USB connector



Communication - 802.15.4 / Zigbee

- Emerging standard for low-power wireless indoor monitoring and control
- 2.4 GHz ISM band (84 channels), 250 kbps data rate
- O-QPSK modulation (Code Division Multiple Access, CDMA); “plays nice” with 802.11 and Bluetooth

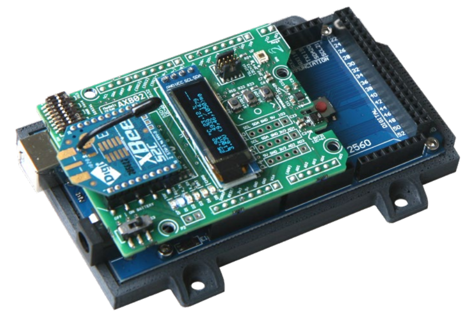
Communication - Standards

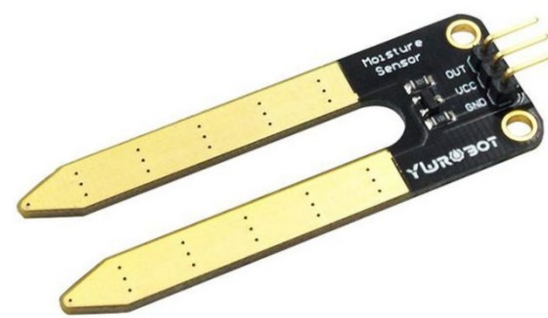


An Application Example

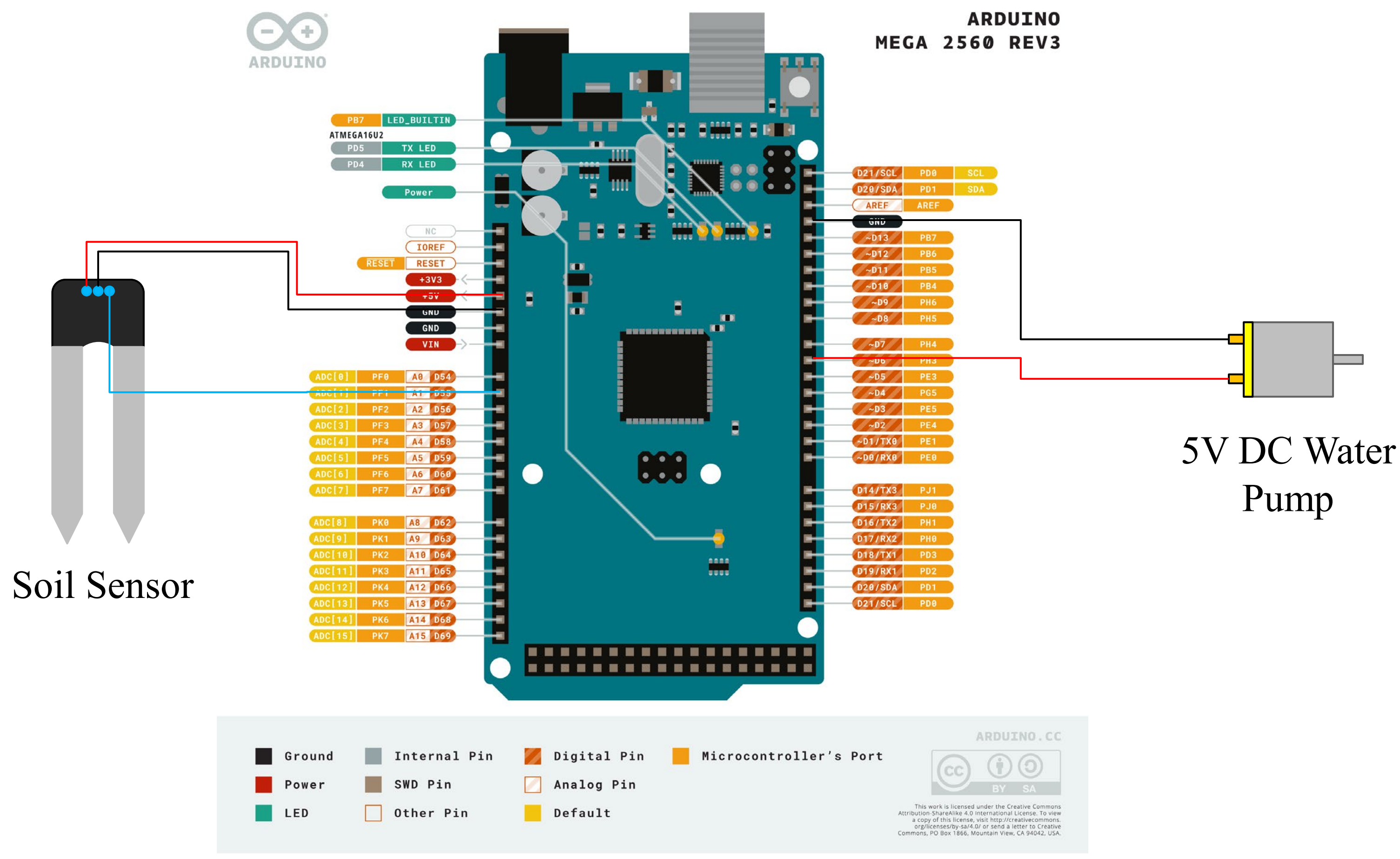
Gardening with Arduino

- Computation -> Arduino board
- Sensor -> Soil moisture sensor
- Actuator -> Water pump
- Communication -> Zigbee
- Power supply -> Battery

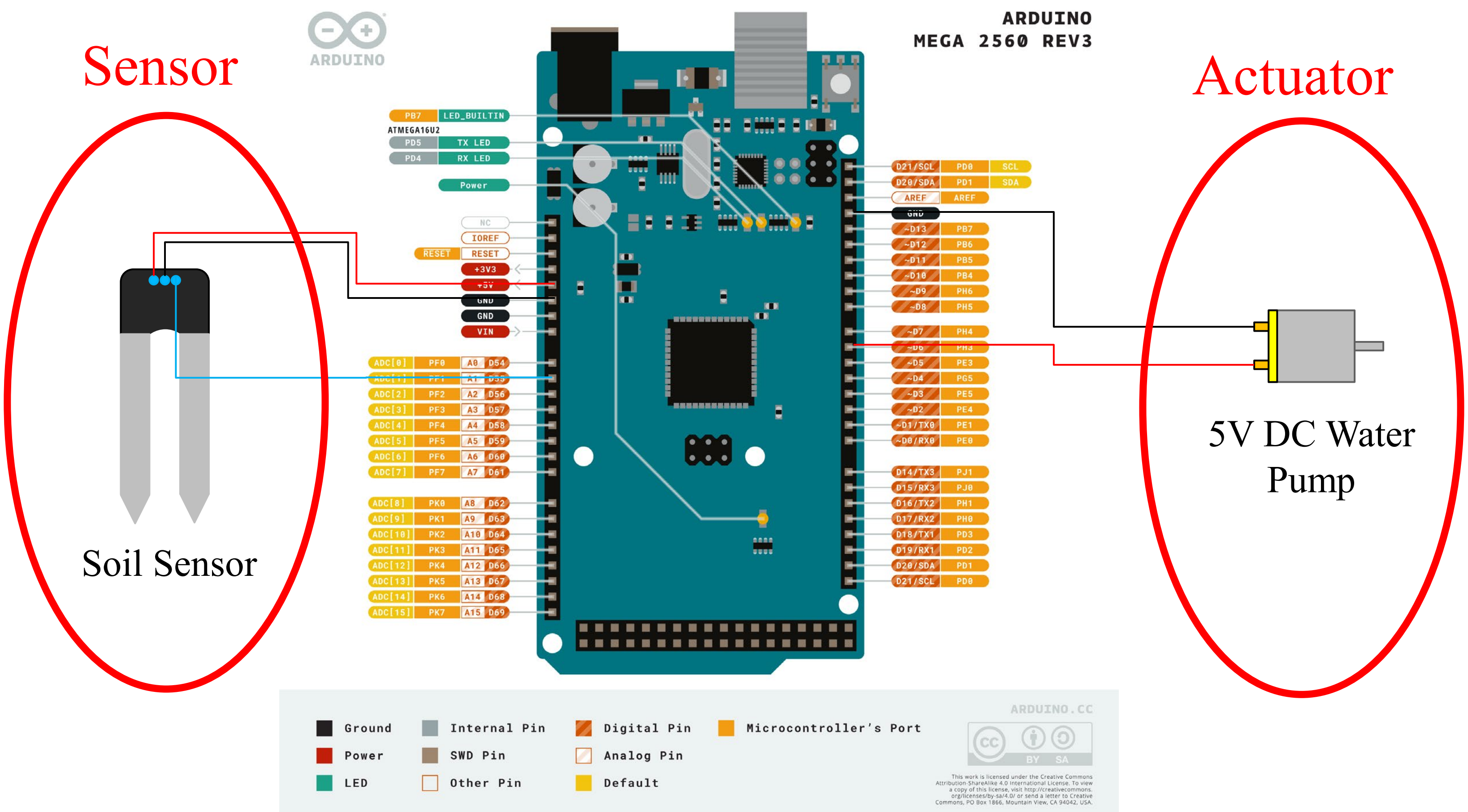




Hardware Connections



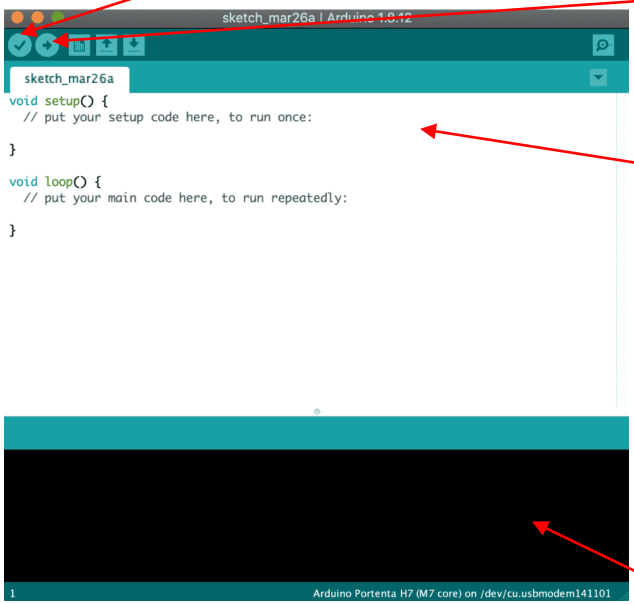
Hardware Connections



Software Development

Compilation step

Upload code to Arduino board



Software to initialize and control sensors, actuators, communication

Depends on the hardware!

Console

Compilation

C

main.c → main

gcc main.c -o main

Source file

```
int main() {
  int a = 5;
  double b = 4.3;
  return a * b;
}
```

Executable (binary)

```
10100101010010
10100101001010
10010100101001
00010101001111
00100101010100
```

Arduino

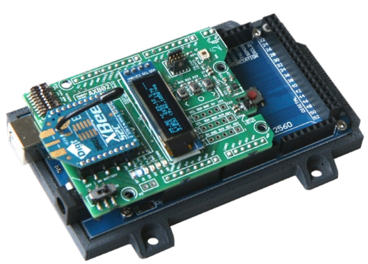
sketch.ino → Verify → Upload

Source file

```
//libraries here
void setup(){
  //setup code, runs once
}
void loop(){
  //implementation code
}
```

- Does the program fit the target board?
- Any syntax mistakes?

Load the sketch on the board



Power in Embedded Systems

Motivation

- Energy is one of the key bottlenecks for autonomous/unattended operation of embedded systems
- Field instruments as examples of embedded systems operating in extreme conditions; a few considerations on:
  - Power consumption
  - Power generation
  - Power storage

Power Consumption

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Power

$$P = U \cdot I$$

Examples:

- MICAz:
  2 * 1,5V battery, 25 mA power consumption → 2*1,5V*0,025A=**80mW** (standby: **80 µW**)

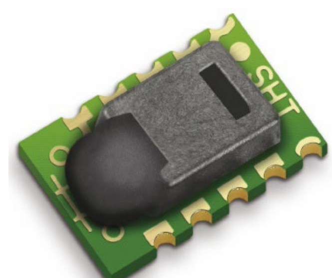
- Campell Scientific: 3D ultrasonic anemometer: **1,2W or 2,4W**

2.4 Power Requirements

VOLTAGE SUPPLY: 10 to 16 Vdc

POWER:
2.4 W @ 60 Hz measurement frequency
1.2 W @ 20 Hz measurement frequency

- SHT1x temperature and humidity sensor: **2µW – 3mW**



Electrical and General Items

Parameter	Condition	min	typ	max	Units
Source Voltage		2.4	3.3	5.5	V
Power Consumption [5]	sleep		2	5	µW
	measuring		3		mW
	average		150		µW
Communication	digital 2-wire interface, see Communication				
Storage	10 – 50°C (0 – 125°C peak), 20 – 60%RH				

Energy

$$E = P \cdot t$$

Examples:

- Rechargeable battery (NiMH):
  1,2V*2000mAh=2400mWh=**2,4Wh**

- Rechargeable battery (LiPo):
  3,7V*1340mAh=4958mWh=**4,958Wh**

Energy in the International System of Units: **Joule**

1 Joule = 1 Ws

Factors Influencing the Power Consumption of an Instrument

- **Hardware choices**
  - Sensing, actuation, communication principles and related technology
  - Computation resources and speed
  - Low-power and high-power general-purpose electronic components (e.g., microcontrollers, transceivers, ADC/DAC)
  - …
- **Software choices**
  - Instrument software architecture
  - Power-aware algorithms controlling the various sensing, actuation, communication and computation modules (e.g., balancing sleep vs. active mode, information flow control)
  - …

Sensing Technology Choices

Consumption vs. capabilities (example 1):

- Disdrometer 1 ("tipping bucket") (≈ 0W)
  - no snow, sleet
  - no robust to freezing
  - no drop statistics
  - resolution
- Disdrometer 2 (laser) (≈ 10W)
  + snow, sleet
  + robust to freezing
  + drop statistics
  - expensive
  - delicate
- Disdrometer 3 (hot plate) (≈ 100W)
  + snow, sleet
  + robust freezing
  + simple
  - drop statistics

Sensing Technology Choices

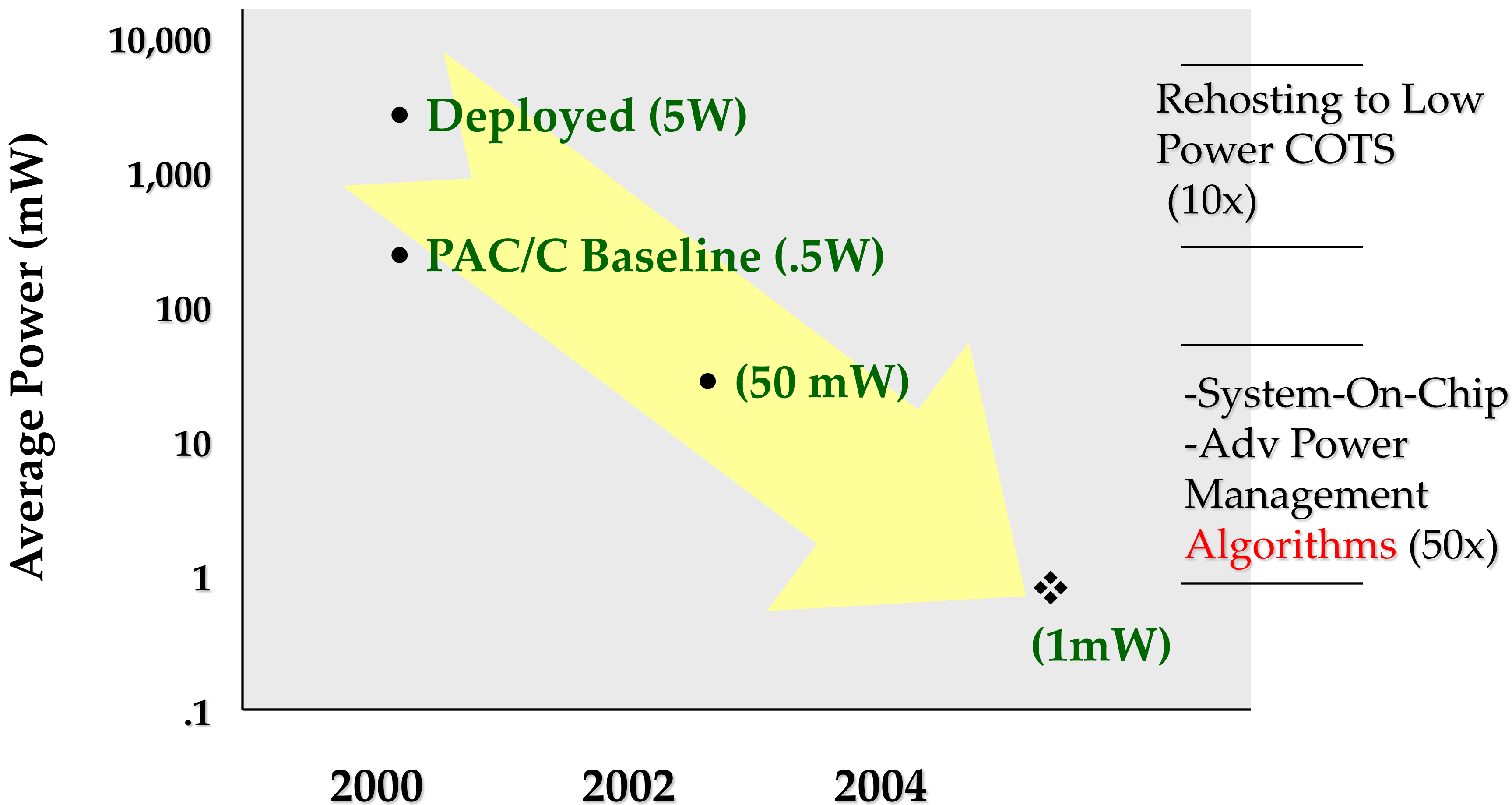
Consumption vs. capabilities (example 2):

- Anemometer 1 (cup) (≈ 0W)
  - 1D (main direction)
  - no robust to freezing
  - temporal resolution (0.3 Hz)
  - minimal wind speed high

- Anemometer 2 (ultrasonic) (≈ 10W)
  + 2D
  + *some* snow, sleet
  + *some* robustness to freezing
  + temporal resolution (up to 60Hz)
  - expensive
- Anemometer 3 (Anemometer 2+heater) (≈ 100W)
  + 2D
  + snow, sleet
  + robust to freezing
  + temporal resolution
  - expensive

EPFL

Hardware and Software Impact

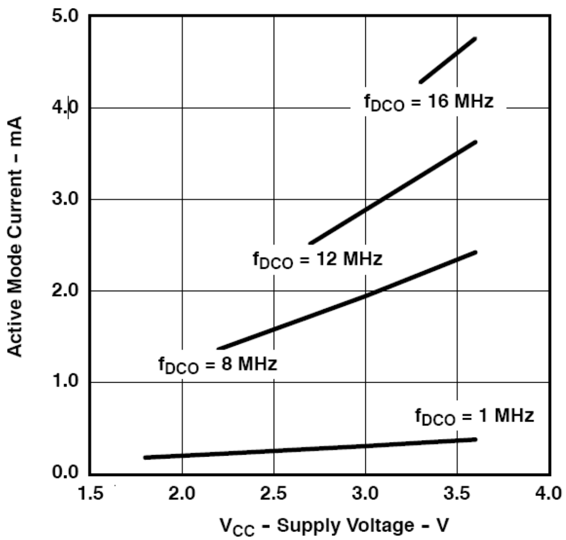


Source: ISI & DARPA PAC/C Program

Computation and Communication

Consumption vs. processing speed:

- $P \sim f_{clock}$
- *Energy/operation = const*



Source: MSP430 data sheet

Consumption vs. transmission power:

- $P=f(P_{RF})$
- sometimes linear: $P \sim P_{RF}$
- often: "sweet spot"

Computation and Communication

	1999 (Bluetooth Technology)	2004
Communication	(150nJ/bit)	(5nJ/bit)
	1.5mW*	50uW
Computation		~ 190 MOPS
		(5pJ/OP)

Source: ISI & DARPA PAC/C Program

Assume: 10kbit/sec. Radio, 10 m range.

Large cost of communication relative to computation continues

Power Generation

Power Generation Methods

- Solar
- Wind
- Temperature difference (Seebeck Effect)
- Vibration
- Hydro


Solar Power Generation

1000W

150W

135W

1000W/m^2

Efficiency: 10-20%

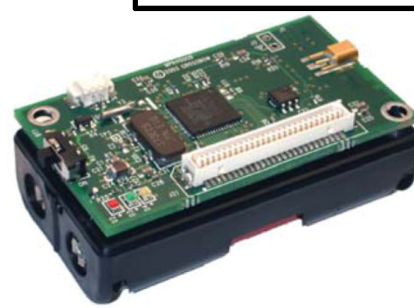
Efficiency: 90%

Efficiency: 70%

95W

Efficiency: 90%

85W



Solar Power Generation

100W

1m^2

15W

13,5W

100W/m^2

Efficiency: 10-20%

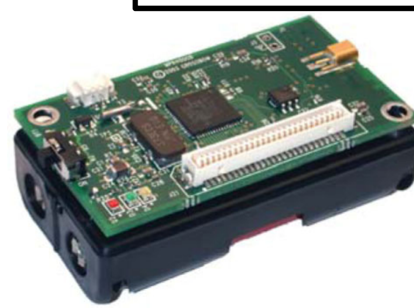
Efficiency: 90%

Efficiency: 70%

9,5W

Efficiency: 90%

8,5W



0,1m^2 per W (e.g., 32 x 32 cm^2)

Power Storage

Batteries

- primary (non rechargeable, red)
  "often a good idea"
- secondary (rechargeable, blue)

Battery Type	Cost $ per Wh	Wh/kg	Joules/kg	Wh/liter
Lead-acid	$0.17	41	146,000	100
Alkaline long-life	$0.19	110	400,000	320
Carbon-zinc	$0.31	36	130,000	92
NiMH	$0.99	95	340,000	300
NiCad	$1.50	39	140,000	140
Lithium-ion	$4.27	128	460,000	230

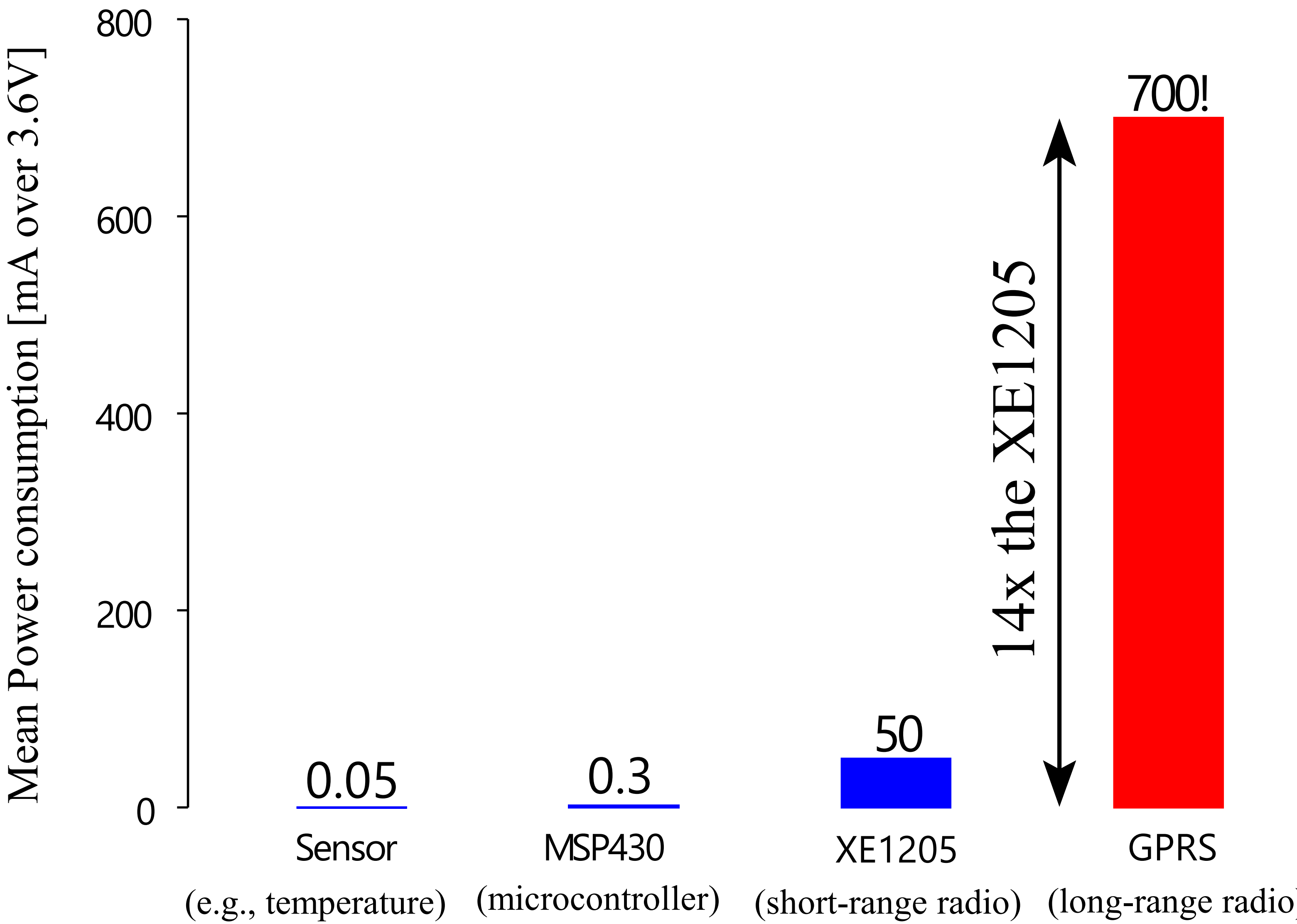
- Other important parameters:
  - number of cycles (few 100 – few 1000) optimal conditions
  - cold temperature behavior
- Interesting alternative: super capacitor
  - 30 Wh/kg
  - expensive
  - very high number of cycles (> 100'000)

Example: Power in a SensorScope Station

Power Generation and Storage

- 162x140mm solar panel
- 12Ah NiMH rechargeable battery
- Based on s. 50 estimation and panel size: average consumption < 220 mW for battery level maintenance.

Power Consumption



Power Consumption – Battery Depletion Without Charging

- With NiMH batteries (nominal voltage 1.2 V), 12 Ah, total energy 14.4 Wh (see s. 34), and only one of the components below always active, the battery will be depleted in:
  - Sensor: **9 years**
  - MSP430: **1.5 years**
  - Short-range radio: **3 days**
  - Long-range radio: **6 hours**

Power Management – Battery Maintenance with Solar Panel Charging

- Basic functionalities (sensing and computation):
  (0.05+0.3) mA *3.6 V= 1.26 mW << 220 mW, ok
- Basic functionalities + short-range radio:
  (0.05+0.3+50) mA *3.6V = 181 mW < 220 mW, acceptable but reduced margin (e.g., critical with long rainy periods, additional sensors attached)
- Basic functionalities + long range radio:
  (0.05+0.3 + 700) mA *3.6V = 2521 mW >> 220 mW, immediate battery depletion

- Solution: power-aware management of the resources (e.g., switching on short/long range radio only when needed)

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 functional modules of an embedded system: perception, computation, communication, actuation, power supply
- Some key concepts in perception: proprioceptive and exteroceptive sensors; active and passive sensors; accuracy and precision
- Power is most often the key design constraint in embedded systems, even more for field embedded systems/instruments if operating in unattended mode
- Not only appropriate hardware design choices but also efficient power management software strategies can decrease the consumption by several orders of magnitude
- Power is comparably difficult to generate and store

Additional Literature – Week 6

Books

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