Signals, Instruments, and Systems – W6

Introduction to Embedded Systems – Terminology, Perception, and Power
Outline

• Embedded systems
  – Motivation
  – Terminology, key concepts, and examples
  – Perception and sensors

• Embedded systems used in the course

• Power and energy 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.

In-situ instrument → Transportation channel → Base station
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.
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-base station)
- **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)
Action - Actuators

• Not always present in embedded systems
• Actuator examples: motors, heaters, pumps, valves
• 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

- e-puck robot
- DISAL Arduino Node
- Sensorscope station
- 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

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

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

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

[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

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

Note: see also W4 lecture on magnitude in Bode plots

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

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

[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 for frequency response
  • nonlinearities can be compensated/inverted digitally

\[ x \rightarrow f(x) \]
\[ y \rightarrow f(y) \]
\[ \alpha \cdot x + \beta \cdot y \rightarrow f(\alpha \cdot x + \beta \cdot y) = \alpha \cdot f(x) + \beta \cdot f(y) \]

[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 a possibly LTI 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

\[
\text{accuracy} = 1 - \left( \frac{|m - v|}{v} \right)
\]

\(m = \text{measured value}\)
\(v = \text{true value}\)

[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
  

\[ \text{precision} = \frac{\text{range}}{\sigma} \]

\[ \sigma = \text{standard dev of the sensor noise} \]

[From *Introduction to Autonomous Mobile Robots*, Siegwart R. and Nourbakhsh I. R.]
Educational Embedded System used in the Course
DISAL Arduino Xbee Node

- Arduino Mega 2560 board (ATMega 2560 microcontroller)
- Zigbee-complaint transceiver (Xbee)
- On-board mini-display
- Sensors:
  - Light sensor (TSL2561-T, ams)
  - Humidity and Temperature sensor (SHT20, Sensirion)
  - Digital Accelerometer (MMA8652, NXP)
- 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

Complexity/power/cost

Data rate

- Bluetooth
- 802.15.4 Zigbee
- CC1000

- 802.11b: 11 Mbps, 720 kbps, 250 kbps, 38.4 kbps
- 802.11g: 54 Mbps
- 802.11a
Power Management in Field Instruments
Motivation

• Energy is one of the key bottlenecks for autonomous/unattended operation of embedded systems

• Field instruments as extreme examples
  – Power consumption
  – Power generation
  – Power storage
Power Consumption
$$P = U \cdot I$$

Examples:

• MICAz:
  2 * 1.5V battery, 25 mA power consumption → $2 \times 1.5V \times 0.025A = 80 \mu W$
  (standby: 80 µW)

• Campell Scientific:
  3D ultrasonic anemometer:
  1.2W or 2.4W

• SHT1x temperature and humidity sensor:
  2µW – 3mW

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

Electrical and General Items

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Condition</th>
<th>min</th>
<th>typ</th>
<th>max</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source Voltage</td>
<td></td>
<td>2.4</td>
<td>3.3</td>
<td>5.5</td>
<td>V</td>
</tr>
<tr>
<td>Power Consumption $^5$</td>
<td>sleep</td>
<td>2</td>
<td>5</td>
<td></td>
<td>µW</td>
</tr>
<tr>
<td></td>
<td>measuring</td>
<td>3</td>
<td></td>
<td>5</td>
<td>mW</td>
</tr>
<tr>
<td></td>
<td>average</td>
<td>150</td>
<td></td>
<td></td>
<td>µW</td>
</tr>
<tr>
<td>Communication</td>
<td>digital 2-wire interface, see Communication</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Storage</td>
<td>10 – 50°C (0 – 125°C peak), 20 – 60% RH</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Energy

\[ E = P \cdot t \]

Examples:

- Rechargeable battery (NiMH):
  \[ 1.2V \times 2000mAh = 2400mWh = 2.4Wh \]

- Rechargeable battery (LiPo):
  \[ 3.7V \times 1340mAh = 4958mWh = 4.958Wh \]

- Communication and computation energy:
  (remember 1 Ws=1 Joule)
<table>
<thead>
<tr>
<th>1999 (Bluetooth Technology)</th>
<th>2004</th>
</tr>
</thead>
<tbody>
<tr>
<td>Communication</td>
<td></td>
</tr>
<tr>
<td>(150nJ/bit)</td>
<td>(5nJ/bit)</td>
</tr>
<tr>
<td>1.5mW*</td>
<td>50uW</td>
</tr>
<tr>
<td>Computation</td>
<td>~ 190 MOPS</td>
</tr>
<tr>
<td></td>
<td>(5pJ/OP)</td>
</tr>
</tbody>
</table>
Managing Power Consumption

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
Managing Power Consumption

Consumption vs. capabilities (example 2):

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

- Anemometer 2 (ultrasonic) ($\approx 10W$)
  + 2D
  + *some* snow, sleet
  + *some* robustness to freezing
  + temporal resolution
    (up to 60Hz)
  - expensive

- Anemometer 3 (Anemometer 2+heater) ($\approx 100W$)
  + 2D
  + snow, sleet
  + robust to freezing
  + temporal resolution
  - expensive
Sensor Node Energy Roadmap

- Deployed (5W)
- PAC/C Baseline (.5W)
  - (50 mW)
  - (1mW)

- Rehosting to Low Power COTS (10x)
- System-On-Chip
- Adv Power Management Algorithms (50x)

Source: ISI & DARPA PAC/C Program
Managing Power Consumption

Consumption vs. processing speed:

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

Consumption vs. transmission power:

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

Source: MSP430 data sheet
### Communication/Computation Technology Projection

<table>
<thead>
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<th></th>
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<th>2004</th>
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<tbody>
<tr>
<td><strong>Communication</strong></td>
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<td></td>
<td>1.5mW*</td>
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<tr>
<td><strong>Computation</strong></td>
<td>~ 190 MOPS</td>
<td>(5pJ/OP)</td>
</tr>
</tbody>
</table>

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

**Large cost of communication relative to computation continues**
Power Consumption in Wireless Communication
Power

• Increased power
  – higher throughput
  – higher range
  – mobile systems: shorter battery life
  – increased health risk (?)

• Regulation
  – CH: OFCOM
  – e.g., WLAN: 100 mW
Power

• Unit: W (Watt)
  – Often written in dBm (decibels to 1 mW)

\[ P_{dBm} = 10 \log_{10}(P_{mW}) \]

• Gain / loss: factors
  – Often written in dB (decibels)

\[ F_{dB} = 10 \log_{10}(F) \]
$P_{dBm}$ and Gain/Loss factors

$$P_{dBm} = 10 \log \left( \frac{P_w}{1\text{mW}} \right)$$

- 1mW → $10 \log(1\text{mW}/1\text{mW}) \rightarrow 10 \log(1) = 10 \cdot 0 = 0 \text{ dBm}$
- 2mW → $10 \log(2\text{mW}/1\text{mW}) \rightarrow 10 \log(2) \approx 10 \cdot 0.3 = 3 \text{ dBm}$
- 10mW → $10 \log(10\text{mW}/1\text{mW}) \rightarrow 10 \log(10) = 10 \cdot 1 = 10 \text{ dBm}$
- 100mW → $10 \log(100\text{mW}/1\text{mW}) \rightarrow 10 \log(100) = 10 \cdot 2 = 20 \text{ dBm}$

Factors in the chain become sums in a log form:
$\log(x \cdot y) = \log(x) + \log(y)$
## Link Budget

### Typical WLAN link budget (100 m, dipole antennas):

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
<th>Margin 23 dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>TX power</td>
<td>100 mW</td>
<td>20 dBm</td>
</tr>
<tr>
<td>TX losses</td>
<td>*0.5</td>
<td>-3 dB</td>
</tr>
<tr>
<td>TX antenna gain</td>
<td>*1.6</td>
<td>+2 dB</td>
</tr>
<tr>
<td><strong>Free space path loss</strong></td>
<td><em>1.0106</em>10^-8</td>
<td>-80 dB</td>
</tr>
<tr>
<td>RX antenna gain</td>
<td>*1.6</td>
<td>+2 dB</td>
</tr>
<tr>
<td>RX losses</td>
<td>*0.5</td>
<td>-3 dB</td>
</tr>
</tbody>
</table>

### Calculated Values

<table>
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<tr>
<th>Component</th>
<th>Value</th>
<th>Margin 23 dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>RX power</td>
<td>0.000000064 mW</td>
<td>-62 dBm</td>
</tr>
<tr>
<td>RX sensitivity</td>
<td>0.0000000003 mW</td>
<td>-85 dBm</td>
</tr>
<tr>
<td>Margin</td>
<td>200</td>
<td>23 dB</td>
</tr>
</tbody>
</table>
Free Space Path Loss (Friis Law)

• Signal power decay in air:

\[ L = \left( \frac{4\pi df}{c} \right)^2 \]

\[ L_{dB} = 20 \log_{10}(d) + 20 \log_{10}(f) - 147.56 \]

• Proportional to the square of the distance \( d \)
• Proportional to the square of the frequency \( f \)
  – high frequency = high loss
  – low frequency = low throughput
DISAL Arduino Xbee vs. SensorScope Station

DISAL Arduino Xbee kit
• Microcontroller:
  • ATMega 2560

• Transceiver:
  • Silicon Labs EM357 (part of the Xbee 802.15.4 module)
  • 2.4 GHz carrier
  • Throughput: up to 250 kbps
  • Range: up to 90 m

SensorScope Data Logger
• Microcontroller:
  • TI MSP430

• Transceiver:
  • Semtech XE 1205
  • 868 and 915 MHz carriers
  • Throughput: up to 153 kbps
  • Range: up to 2 km
Power Generation
Power generation methods

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

1000W/m²  Efficiency: 10-20%

150W  Efficiency: 90%

135W  Efficiency: 70%

95W  Efficiency: 90%

85W
Solar Power Generation

100W
1m²

100W/m²
Efficiency: 10-20%

15W
Efficiency: 90%

13.5W
Efficiency: 70%

9.5W
Efficiency: 90%

0.1m² per W (e.g., 32 x 32 cm²)

8.5W
Power Storage
Batteries

• primary (non rechargeable, red)
  “often a good idea”
• secondary (rechargeable, blue)

• 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 Management in a SensorScope Station
Power Generation and Storage

- 162x140mm solar panel
- 12Ah NiMH rechargeable battery
- Based on s. 48 estimation and panel size: average consumption < 220 mW for battery level maintenance.
Mean Power consumption [mA over 3.6V]

- Sensor (e.g., temperature): 0.05 mA
- MSP430 (microcontroller): 0.3 mA
- XE1205 (short-range radio): 50 mA
- GPRS (long-range radio): 700 mA

14x the XE1205
With NiMH batteries (nominal voltage 1.2 V), 12 Ah, total energy 14.4 Wh (see s. 33), 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):
  \[(0.05+0.3) \text{ mA} \times 3.6 \text{ V} = 1.26 \text{ mW} \ll 220 \text{ mW}, \text{ ok}\]

- Basic functionalities + short-range radio:
  \[(0.05+0.3+50) \text{ mA} \times 3.6 \text{ V} = 181 \text{ mW} \ll 220 \text{ mW}, \text{ acceptable but reduced margin (e.g., critical with long rainy periods, additional sensors attached)}\]

- Basic functionalities + long range radio:
  \[(0.05+0.3 + 700) \text{ mA} \times 3.6 \text{ V} = 2521 \text{ mW} \gg 220 \text{ mW}, \text{ immediate battery depletion}\]

- **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, sometimes actuation

• 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


Pointers:

• Sensorscope https://www.sensorscope.ch