Smart Sensors

Overview

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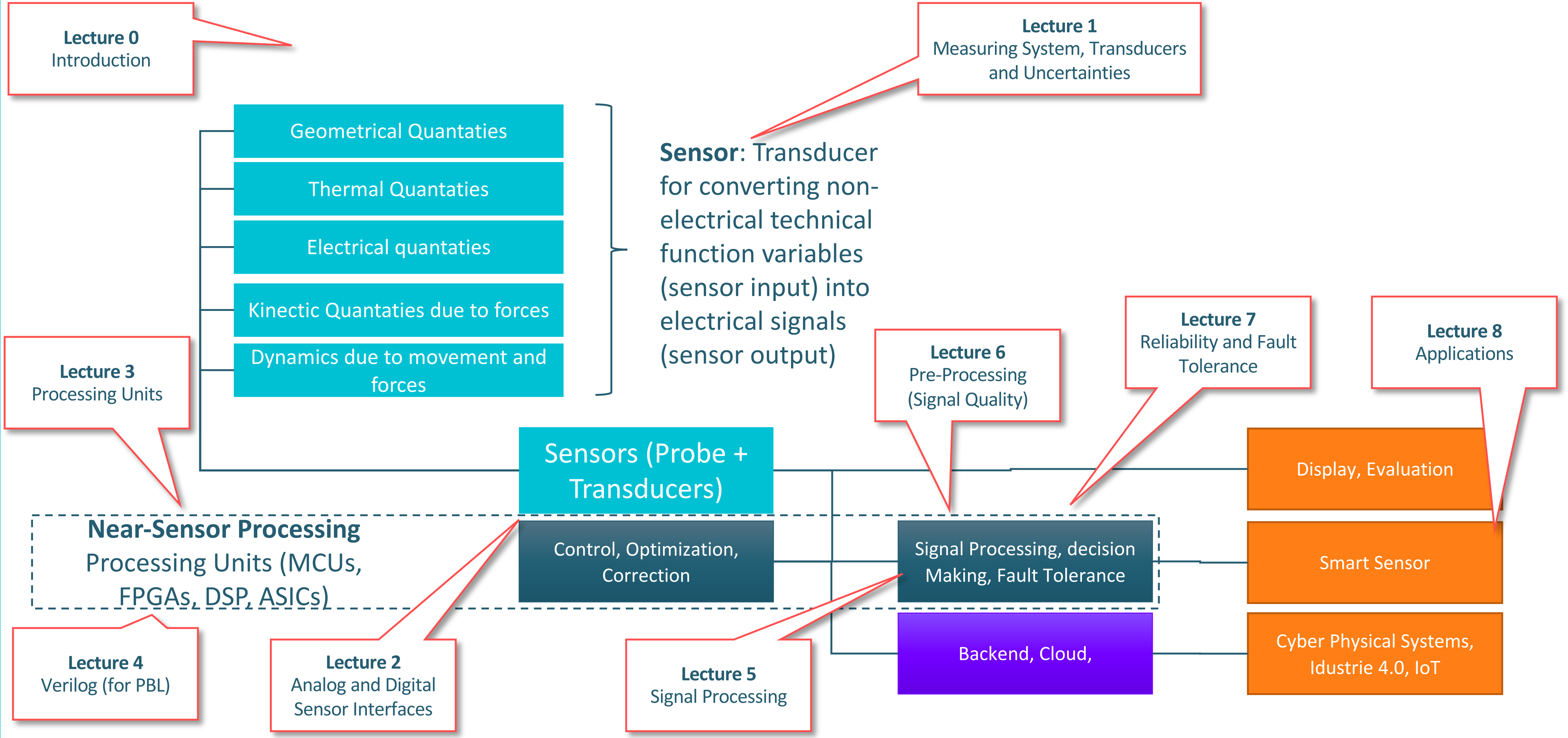
Smart Sensor - Topics in the Lecture



Lecture 0: Introduction

- General objectives
- Structure of the course
  - Lecture, PBL
  - Timeline
- Evolution of Sensors
  - Towards Smart Sensors, difference between IoT
  - Growing computational complexity (moore‘s law) vs. Limited communication bandwidth → Smart Sensors
- Example of Smart Sensor
- Details regarding PBL → Focus on “Building Smart Sensor System with ULP FPGA“
  - Structure, HW, etc.

Lecture 0: Further Reading

- https://www.intel.com/content/www/us/en/silicon-innovations/moores-law-technology.html
- Kulau, Ulf, et al. "Dynamic sample rate adaptation for long-term IoT sensing applications." *2016 IEEE 3rd World Forum on Internet of Things (WF-IoT)*. IEEE, 2016.
- Kulau, Ulf, et al. "REAPer—Adaptive Micro-Source Energy-Harvester for Wireless Sensor Nodes." *2017 IEEE 42nd Conference on Local Computer Networks Workshops (LCN Workshops)*. IEEE, 2017.
- https://siliconangle.com/2021/04/10/new-era-innovation-moores-law-not-dead-ai-ready-explode/
- Sotenga, Prosper Z., Karim Djouani, and Anish M. Kurien. "Media access control in large-scale Internet of Things: a review." *IEEE Access* 8 (2020): 55834-55859.

Lecture 1: Measuring System, Transducers and Uncertainties

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- Historical Background, SI Units, Technical Quantaties, other subjective units
- Sensor Probes
  - Temperature
  - Motion Sensor → resistive, capacitive, opto-electronics
    - Range measurement, Ultrasonic
  - Force measurement → piezo electric, spring + motion sensor, strain gauge
- Biosensors
  - Analyt + Enzym → Transducer
  - Bioreceptor (Canaries in coal mine…)
  - Indirect Bio-Sensor → Potato Bug etc.
- Uncertainties in measurements
  - Random error + systematic error
  - Error propagation
- Correction of measurement errors
  - Linearization → difference calculation, inversion, lookup tables
  - Dynamic characteristics → transients, overshoots

Lecture 1: Further Reading

- Czichos, Horst. *Mechatronik: Grundlagen und Anwendungen technischer Systeme*. Springer-Verlag, 2015.
- Czichos, Horst, and Werner Daum. "Messtechnik und Sensorik." *Dubbel*. Springer, Berlin, Heidelberg, 2007. W1-W37.
- Iso, I., and BIPM OIML. "Guide to the Expression of Uncertainty in Measurement." *Geneva, Switzerland* 122 (1995): 16-17.
- Hoffmann, Jörg, and Fachbuchverlag Leipzig im Carl-Hanser-Verlag. *Taschenbuch der Messtechnik*. München, 2010.
- Niebuhr, Johannes, and Gerhard Lindner. "Physikalische Meßtechnik mit Sensoren." *tm-Technisches Messen* 63 (1996): 4.
- Kiencke, Uwe, and Ralf Eger. *Messtechnik*. Springer Berlin Heidelberg, 2008. (https://katalog.tub.tuhh.de/Record/1646558138)
- Schroth, Peter. *Biosensoren auf der Basis von Halbleiter-Feldeffektstrukturen mit angekoppelten Insektenantennen*. Diss. Aachen, Techn. Hochsch., Diss., 2000, 2000.

Lecture 2: Analog and Digital Sensor Interfaces

- From analog to digital → simple ADC process
  - sample&hold → Quantization and Encoding
- Sampling Theorem
- Quantization error and ADC Accuracy
- ADC Methods
  - Dual Slope ADC
  - Flash ADC
  - SAR, Successive Approximation
  - Voltage to Frequency → Counter methods
- Digital Sensor Interfaces
  - Parallel vs. Serial
  - UART/USART, Flow Control
  - SPI, Serial Peripheral Interface
  - I2C, Inter integrated circuit
- Issues on multi-sensor systems
  - Timing issue → special HW, DMA support

Lecture 2: Further Reading

- Fraden, Jacob. "Handbook of modern sensors: physics, designs, and applications." (2007).
- Meijer, Gerard, Kofi Makinwa, and Michiel Pertijs. *Smart sensor systems: Emerging technologies and applications*. John Wiley & Sons, 2014.
- Hoffmann, Jörg, and Fachbuchverlag Leipzig im Carl-Hanser-Verlag. *Taschenbuch der Messtechnik*. München, 2010
- Semiconductors, N. X. P. "UM10204 I2C-bus specification and user manual." *User Manual* 4 (2014).
- Leens, Frédéric. "An introduction to I 2 C and SPI protocols." *IEEE Instrumentation & Measurement Magazine* 12.1 (2009): 8-13.
- Oudjida, Abdelkrim Kamel, et al. "Fpga implementation of i 2 c & spi protocols: A comparative study." *2009 16th IEEE International Conference on Electronics, Circuits and Systems-(ICECS 2009)*. IEEE, 2009.
- Dawoud, Dawoud Shenouda, and Peter Dawoud. *Serial Communication Protocols and Standards RS232/485, UART/USART, SPI, USB, INSTEON, Wi-Fi and WiMAX*. River Publishers, 2020.

Lecture 3: Processing Units

- What makes a sensor system smart? → Processing capabilities!
- Processing → Basic principals
  - Comparison MCU, FPGA, ASIC
- MCU
  - Types and architecture, Instruction set, peripherals, …
- Signal Conditioning Ics
  - Architecture example, need e.g. linearization
- DSP
  - Basic idea → accelerate MACs
  - Architecture example
- FPGA
  - ULP FPGAs for Smart Sensors → Motivation, benefits, drawbacks etc.
  - Architecture, principal of working (from PLB to FPGA), LUTs, etc
  - Design flow and ASIC process
  - Example: Internal structure Xilinx vs. Internal structure ICE40
- Combination of processing elements

Lecture 3: Further Reading

- Vansteenkiste, Elias. *New FPGA design tools and architectures*. Diss. Ghent University, 2016.
- Wüst, Klaus. *Mikroprozessortechnik: Grundlagen, Architekturen, Schaltungstechnik und Betrieb von Mikroprozessoren und Mikrocontrollern*. Springer-Verlag, 2010.
- https://www.st.com/en/microcontrollers-microprocessors/stm32f0x0-value-line.html
- https://www.renesas.com/us/en/products/sensor-products/sensor-signal-conditioners-ssc-afe/zssc3224-high-end-24-bit-sensor-signal-conditioner-ic
- Huddleston, Creed. *Intelligent sensor design using the microchip dsPIC*. Elsevier, 2006.
- Wolf, Marilyn. *Computers as components: principles of embedded computing system design*. Elsevier, 2012.
- Smith, Douglas J. *HDL Chip Design: A practical guide for designing, synthesizing and simulating ASICs and FPGAs using VHDL or Verilog*. Doone publications, 1998.
- https://www.latticesemi.com/iCE40

Lecture 4: Introduction to Verilog

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- HDL Verilog, Introduction, Background
- Why HDL?
- Basic Principals
  - Modules, encapsuling of modules etc.
  - Testbench, how to test modules
  - Basic examples
- Verilog instructions (basic overview)
  - Different instructions + examples

Module structure:
- V1 `module, endmodule`
- V2 `input, output, inout`
- V3 `parameter, defparam`
- V4 `always`
- V5 `initial`

Time controls:
- V6 Waiting #
- V7 `at @`
- V8 `wait`

Classic program control :
- V9 `task, endtask`
- V10 `function, endfunction`
- V11 `if, else`
- V12 `?, :`
- V13 `case, casez`
- V14 `while`
- V15 `for`

Variables and constants:
- V16 `integer`
- V17 `wire`
- V18 `reg`
- V19 Arrays s of Variables
- V20 Constants

Operations:
- V21 Arithmetic `+, *` ...
- V22 Compare `==, !=` ...
- V23 Logic `!, &&, ||`
- V24 Bit-wise Logic `~, &, |`
- V25 Concatanation `{ }`
- V26 Shift `<<, >>`

Assignments:
- V27 Blocking Assignment =
- V28 Non-blocking Assignment <=
- V29 `assign` (Permanent Assignment)

Other instructions :
- V30 `` `define ``
- V31 `$display, $write`
- V32 `$finish`

Lecture 4: Further Reading

- Thomas, Donald, and Philip Moorby. *The Verilog® hardware description language*. Springer Science & Business Media, 2008.
- LaMeres, Brock J. *Quick Start Guide to Verilog*. Springer International Publishing, 2019. (https://katalog.tub.tuhh.de/Record/1067372644)
- https://www.asic-world.com/verilog/veritut.html
- Online-Simulators:
  - https://www.jdoodle.com/execute-verilog-online/
  - https://www.edaplayground.com/home
  - https://www.tutorialspoint.com/compile_verilog_online.php

Lecture 5: Signal Processing

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- Signal Processing essentials and examples
  - analysis, modification and/or synthesis (definition) → Algorithms, boolean cumputation, control structures
  - Examples: Ressource contraints, FFT, Neural Network, implications
- Gajski Diagram → Design constraints
- Implementation techniques and number formats
  - Loop-Unrolling, Pipelining, Parallelization, Ressource sharing, Decomposition (looping), retiming, …
  - Number Formats: Fixed/Floating Point, Q-Format, Log Number System
- Elementary Functions and design constraints
  - Motivation: How can we implement elementary functions efficiently?
  - Iterative methods → e.g. utilize convergence, e.g. iteratively find zero
  - Polynomial function → Approximate complex functions with polynomial of different grades
  - Table based methods → Direct ROM mapping (potentially high memory) → combined method (piecewise functions)

Lecture 5: Further Reading

- H. Kaeslin : „*Digital Integrated Circuit Design: From VLSI Architectures to CMOS Fabrication* “, Cambridge University Press, 2008,
- J. Hennessy, D. Patterson: „*Computer Architecture: A Quantitative Approach* “, Morgan Kaufmann, 2. Aufl., 1996,
- J. Hennessy, D. Patterson: „*Computer Architecture: A Quantitative Approach* “, Morgan Kaufmann, 4. Aufl., 2006,
- B. Parhami : „*Computer Arithmetic: Algorithms and Hardware Designs* “, Oxford Univ Press, 2009
- J.-M. Muller: „*Elementary Functions: Algorithms and Implementation* “, Birkhäuser, 2. Aufl., 2006,

Lecture 6: Pre-Processing (Signal Quality)

- Pre-Processing Techniques → Cleansing, Transformation, Reduction, validation
- Oversampling
  - Motivation and oversampling theorem
  - Derivation of oversampling to improve ADC resolution
- Differential sensing
  - Similar to oversampling but parallel
  - Motivation , HW requirements
  - Noise reduction, improved SNR, common mode interference
- Noise reduction with Kalman Filter
  - Theory: Measurement → Update → Predict
  - Example 1D Kalman Filter: Temperature measurement
  - Challenges
- Kalman for Sensor Fusion

Lecture 6: Further Reading

- Hauser, Max W. "Principles of oversampling A/D conversion." *Journal of the Audio Engineering Society* 39.1/2 (1991): 3-26.
- Grewal, Harman. "Oversampling the ADC12 for higher resolution." *Signal* 16 (2006): 1.
- AN118, Improving ADC. "Resolution by Oversampling and Averaging." (2013).
- U.Kulau, Jochen Rust, David Szafranski, Martin Drobczyk, Urs-Vito Albrecht. Differential BCG Sensor System for Long Term Health Monitoring Experiment on the ISS, 2022 International Conference on Distributed Computing in Sensor Systems (DCOSS)
- Alex Becker. 2018. Kalman Filter Overview. https://www.kalmanfilter.net/default.aspx
- Pei, Yan, et al. "An elementary introduction to Kalman filtering." *Communications of the ACM* 62.11 (2019): 122-133.
- Sasiadek, J. Z., and P. Hartana. "Sensor data fusion using Kalman filter." *Proceedings of the Third International Conference on Information Fusion*. Vol. 2. IEEE, 2000.

Lecture 7: Fault Tolerance

- Motivation, examples of fault-tolerant sensor systems / applications
- Definitions:
  - Fault – Error – Failure
  - Origin of faults, types of faults
- Estimation of MTTF
  - Example to calculate the MTTF
  - Failure density and Failure distribution
  - Bathtub Curve
- Redundancy
  - No vs. Hot vs. Cold redundancy
  - Triple Modular Redundancy (TMR) → MTTF? Reliability?
  - Coding: Hamming, Parity, RS
- Self Test
  - Logic build in self test, Self Test on MEMS, Anomaly detection (2-Sigma, Clustering)
- Software Concepts
  - Robust vs. Redundant SW → Backward vs. Forward Recovery

Lecture 7: Further Reading

- Johnson, Barry W. "An introduction to the design and analysis of fault-tolerant systems." *Fault-tolerant computer system design* 1 (1996): 1-8
- Hantos, Gergely, David Flynn, and Marc PY Desmulliez. "Built-in self-test (BIST) methods for MEMS: A review." *Micromachines* 12.1 (2020): 40.
- Martin, L. "Shooman. Reliability of computer systems and networks." (2002).
- Lala, Parag K. *Self-checking and fault-tolerant digital design*. Morgan Kaufmann, 2001.
- Pullum, Laura L. *Software fault tolerance techniques and implementation*. Artech House, 2001.
- Zug, Sebastian, and Jörg Kaiserua. "An approach towards smart fault-tolerant sensors." *2009 IEEE International Workshop on Robotic and Sensors Environments*. IEEE, 2009.

Lecture 8: Application(s)

- Exemplary Smart Sensor Application
  - Motivation, Use-Case Definition, applied methods and techniques, architecture, results,…
- Short introduction to AI for sensor systems (resource constrained devices)
  - Trend embedded AI → Classical algorithms (e.g. presented application) vs. Machine learning approach
  - Framework for MCUs
    - STM32 Cube.ai
    - AIFES
    - Challenges for the resources → again MACs
  - Framework for ULP FPGA
    - Lattice Sense AI
- Gest Lecture will pick up the challenge how to run neural network model efficiently on ressource constrained sensor HW → Example: Power Metering

Lecture 8: Further Reading

- Drobczyk, M., Lübken, A., Strowik, C., Kulau, U., Rust, J., Beringer, J., & Albrecht, U. V. (2021, October). Wireless Compose-2: A wireless communication network with a Ballistocardiography Smart-Shirt experiment in the ISS Columbus module. In *2021 IEEE International Conference on Wireless for Space and Extreme Environments (WiSEE)* (pp. 103-108). IEEE.
- Drobczyk, Martin, et al. "A Wireless Communication Network with a Ballistocardiography Experiment on the ISS: Scenario, Components and Pre-Flight Demonstration." *IEEE Journal of Radio Frequency Identification* (2022).
- U.Kulau, Jochen Rust, David Szafranski, Martin Drobczyk, Urs-Vito Albrecht. Differential BCG Sensor System for Long Term Health Monitoring Experiment on the ISS, 2022 International Conference on Distributed Computing in Sensor Systems (DCOSS)
- https://www.st.com/content/st_com/en/ecosystems/artificial-intelligence-ecosystem-stm32.html
- https://www.ims.fraunhofer.de/de/Geschaeftsfeld/Industry/Industrial-AI/Artificial-Intelligence-for-Embedded-Systems-AIfES.html
- https://www.latticesemi.com/sensAI