Sensor Signal Processing

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Brief Course Profile

Course contents: Basics of sensor signal processing and analysis, feature computation, dimensionality reduction, classification, and optimization

Lecture: Tuesday 10:00 – 11:30, 23-188

Lab: 12/425 and 21/260, time to be announced

Level: Diploma, Master, and PhD students

Course materials:
Lecture slides *for download* as pdf-documents
(http://www.eit.uni-kl.de/) Lehre/Sensorsignalverarbeitung

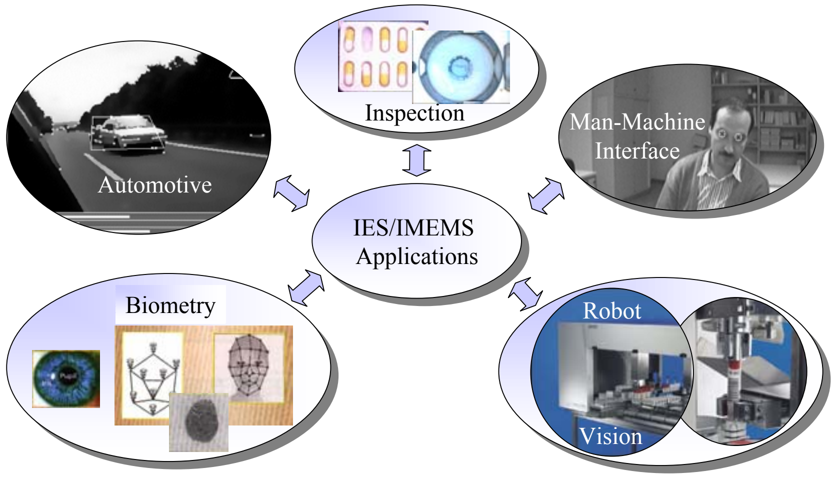
Examination: oral (presentation & discussion of semester project)

Consultations: (koenig@eit.uni-kl.de)

Recommended text books and references:

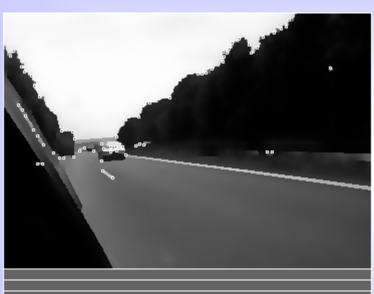
1. R. Hoffmann, *Signalanalyse und Erkennung*, Springer 1998, ISBN 3-540-63443-6
2. S. Haykin, *Neural Networks – A Comprehensive Foundation*, Prentice Hall, 1998, ISBN 0132733501
3. R. Duda, P. Hart, D. Stork, Pattern Classification, Wiley, 2000, ISBN 0471056693

Sensor System Applications



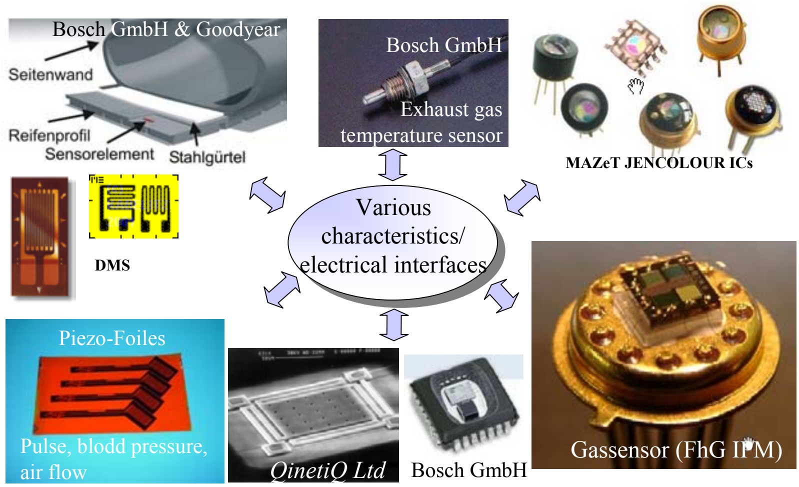
Sensor System Applications

Architectural Study of an Over-Take-Monitor:



- Driver assistance system
- High real-time requirements
- Complex scene
- **Harsh illumination** conditions
- Tough invariance requirements
- Compatibel with car installation
- IES/IMEMS with HW-friendly operators required
- ***Topic of industrial interest !***

Plethora of Sensors



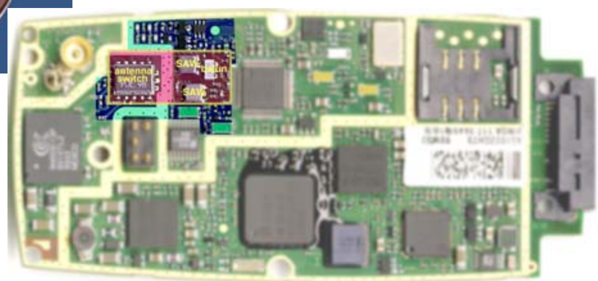
Monolithic or Microsystem/MEMS Integration

Integration Technologies

Single- and multilayer boards (SMD)

Integration Technologies

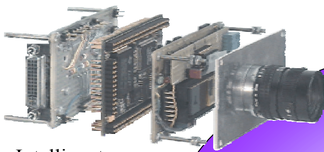
Miniaturized LTCC-Modules



Integration Technologies

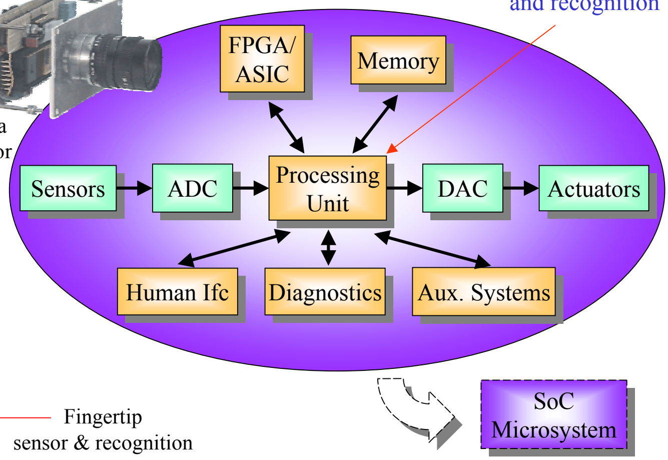
Multichip-Modul (MCM)

Sensor System Architecture



Intelligent camera with CMOS-sensor

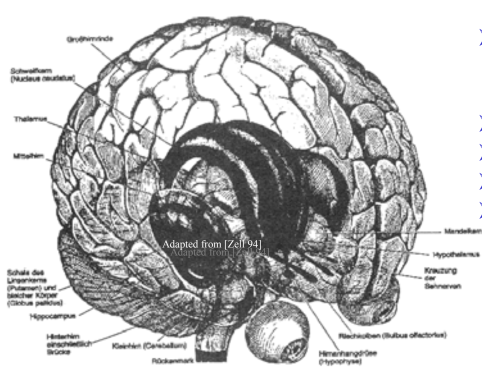
Signal processing and recognition



Fingertip sensor & recognition

Natural vs.Technical Sensing Systems

Intriguing Properties of Human Brain and Nervous System Inspire Computing:



- Neural systems offer attractive capabilities superior to conventional computing
- Massive parallelism
- Invariant signal processing
- Learning & adaptation
- Robustness & fault-tolerance due to self-repair capability

⇨ Sensing, Recognition, Understanding, Acting

Processing chain in conventional sensing & recognition systems:

Sensing → Feature-computation → Dimension reduction → Classifier Training/Test → Classification results

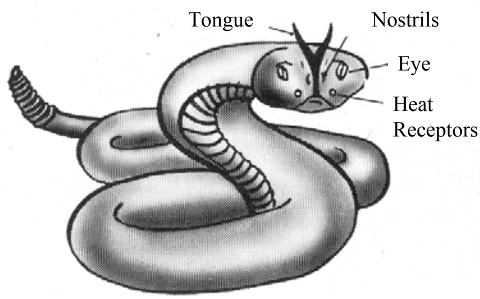
Design of Recognition System

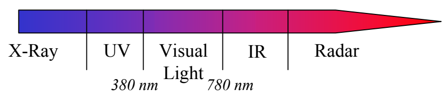
- Application-Specific Acquisition & Processing of Multisensor Data

<u>Senses of Living Beings</u>
Sense of Taste
Olfaction
Sense of Touch
Audition
Vision

⇩

<u>Technical Models</u>
Sensor Technology
MEMS
Microelectronic



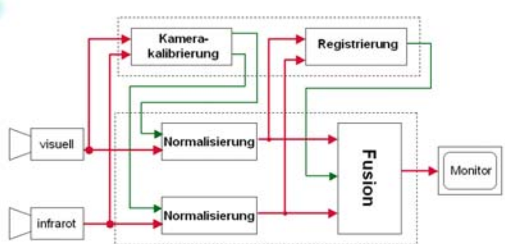


Most Complex Sense: Vision

Design of Recognition System

- Application-Specific Acquisition & Processing of Multisensor Data

<u>Night-Vision in Automotive Applications*:</u>

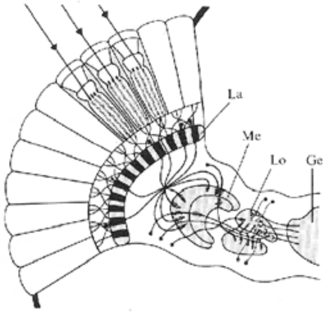


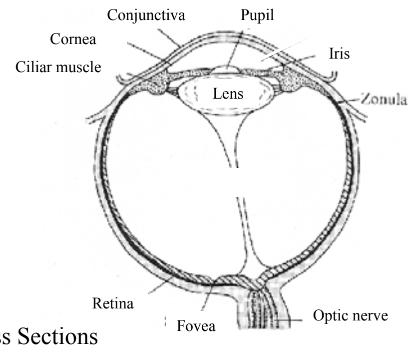
- **Information unique to visual/IR domain**
- **Appropriate Sensor Fusion required**
- **Embedded real-time capable solution mandatory**

*Courtesy BMW AG, Munich, T. Weidner, H. Hahn

Design of Recognition System

- Application-Specific Expenditure of Resources





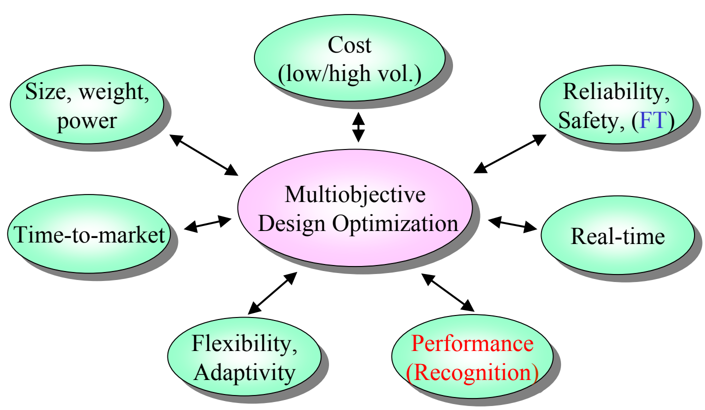
Cross Sections

Fly´s Eye

Human Eye

- **Technical spectrum:** Photoelectric barrier to special purpose camera
- **Options:** Sensor/spatial resolution, rate, color, stereo (depth), motion, IR

Design of Recognition System

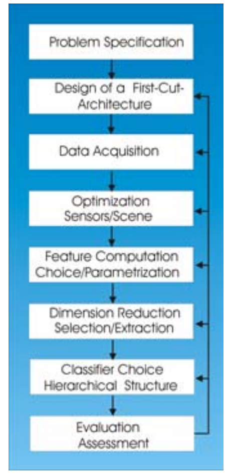


- Appropriate methodology and flow for viable & feasible design mandatory
- **Approach:** Bio-inspired *adaptive* circuits & systems (*integrated HW/SW*)

Design of Recognition System

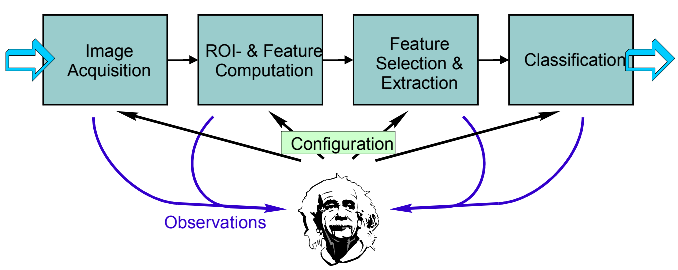
Challenges of Intelligent System Design:

- Requires substantial engineering effort
- Dominantly manual and intuitive task
- Time, labour, and cost intensive
- Strong diversity of available methods & tools (from signal processing to *Soft-Computing)*
- Requires experienced and qualified staff
- State-of-the-art: IC design 20 years ago
- Design style: *Full-Custom*
- **DA:** Only emerging for visual inspection
- No interface to standard chip design hierarchy



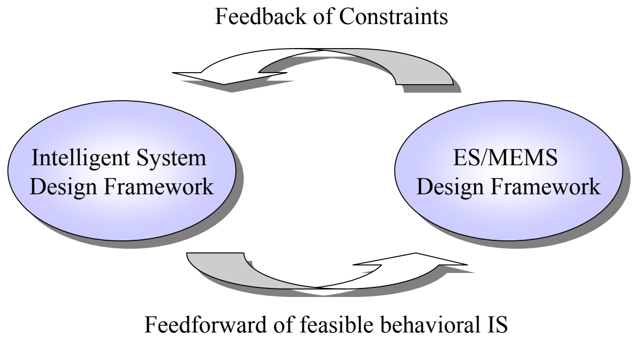
Design of Recognition System

Typical Image Processing and Recognition System Design:



- **DA required:** Toward semi-custom or system synthesis design style
- **Learning approach** draws from multiple sources of bio-inspiration
- **Vision**: From optimization/learning in the design phase to on-line adaptation & self-repair

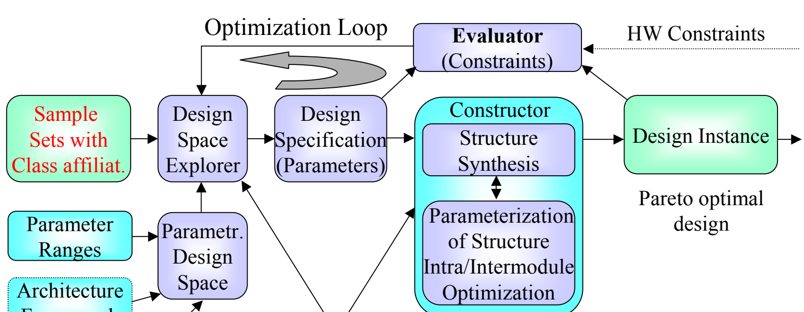
Design of Recognition System



- Linking the Frameworks of IS & ES design using multiobjective optimization
- Merging SW & HW development by chosen information processing paradigm
- *Long term: Migrate from design-time to run-time optimization/adaptation*

Design of Recognition System

- Holistic Modelling and Design Methodology

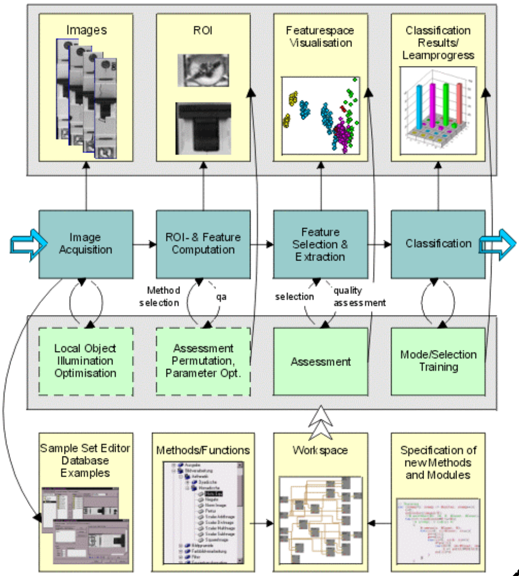


- Application-specific design
- Learning Paradigm: *Learning from examples* or experience
- Constraint feedback, e.g., numerical resolution/bits

Design of Recognition System

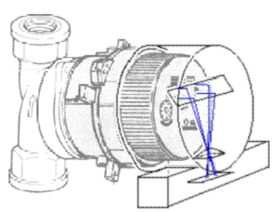
QuickCog Environment:

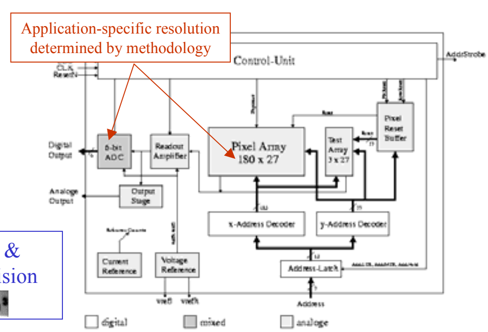
- Fast & consistent design
- Assessment and optimization
- Intra/inter level optimization
- Holistic modelling and simulation
- Opportunistic & parsimonious
- DR (AFS) salience:
  physical savings !



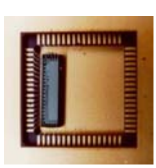
Application Examples

- Automatic Visual Consumption Control



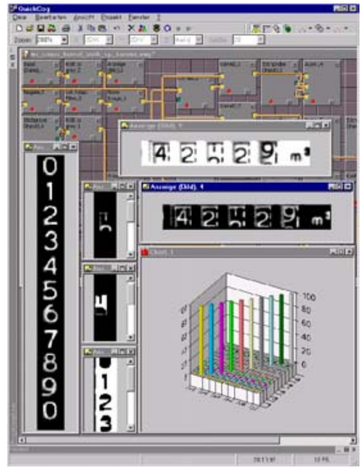


Visual consumption registration & interpretation in an embedded vision system (SoC)



Application Examples

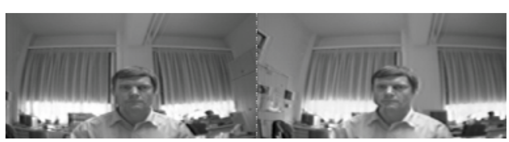
Template matching approach applied in two industrial feasibility studies



Application Examples

Eye-Tracker for 3D-Display Control (TU Dresden, CS, AI Inst. D4D-Group):

- To achieve 3D-perception for system user, eye positions must be tracked
- Embedded solution required
- Stereo CCDs and TI 320C82 on dedicated board & SW by D4D-Group



- CCD properties not satisfactory for harsh illumination conditions (game halls)
- Low-power, low-cost deeply embedded solution aspired
- Higher performance aspired: recognition/tracking, multiple users

Application Examples

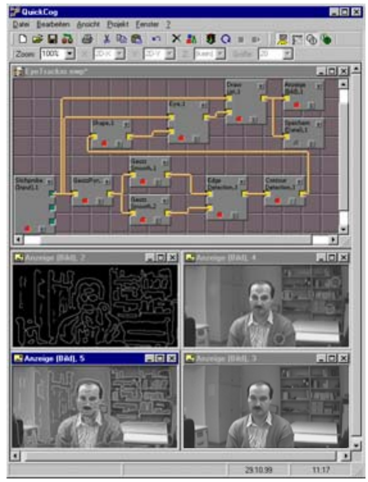
Eye-Tracker Research Vehicle:

- Monofocal modelling
- HDR CMOS-Sensor with integrated signal processing
- Low-power analog/mixed design
- Close relation to automotive tasks !

Selective Attention → Face/Eye Location → Feature List → Feature Tracking → 3D-Display Control

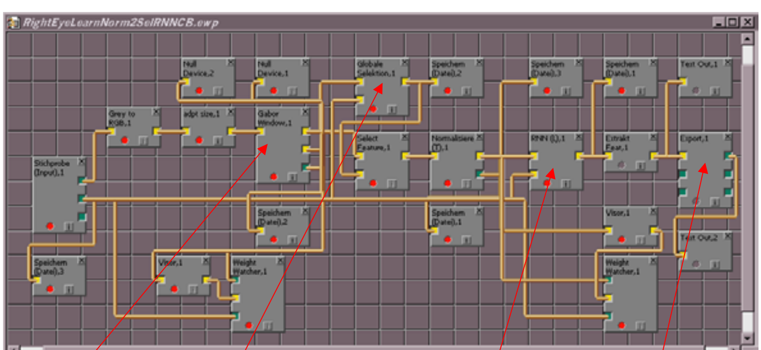
Difference Image
Symmetry
Multi-scale Proc.

Features:
Gabor jets
Loc. autocorr.
Loc. orient.
Classification:
RNN, RBF,



Application Examples

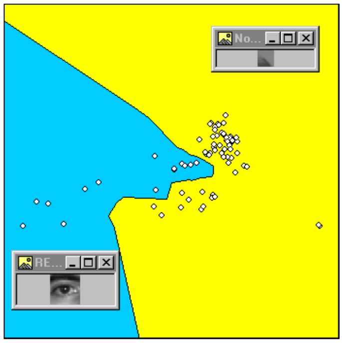
Subtask: Eye-Shape Classification:

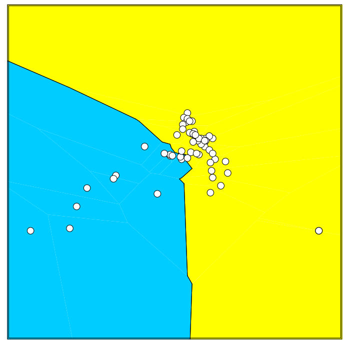


Gabor-Jets
AFS
Verilog-A for DFW II
RNN-Classifier with constrained Manhattan Metric

Application Examples

- Eye-Shape Classification Using Gabor Jets:





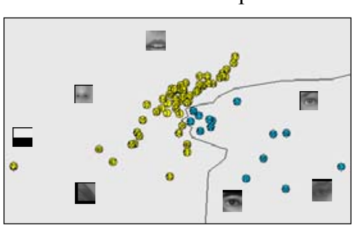
- AFS chooses feature 2, 4, 6, 7, 8, and 12 from 12-D Gabor-Jet
- Recognition results of 100% (one pattern very close to error)
- These features were used for RNN classifier implementation work

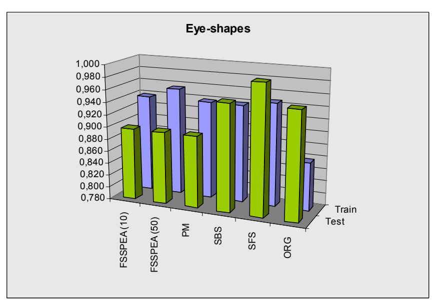
Application Examples

Eye-Tracker Results:

- SFS best/stable solution
- Generalization is affected by dimensionality reduction
- SFS solution for HW-design

Reduced feature space

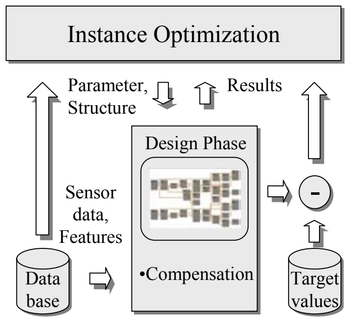




Method	Train	Test	Features
ORG	0,858374	0,953647	12
SFS	**0,94704**	**0,989362**	**6**
SBS	0,93842	0,953647	6
PM	0,93842	0,896657	4
FSSPEA (50)	*0,95567*	*0,896657*	*3*
FSSPEA (10)	*0,93842*	*0,896657*	*4*

Application Examples

- Real-World-Problem: Medical Tube Classification (M. Eberhardt)

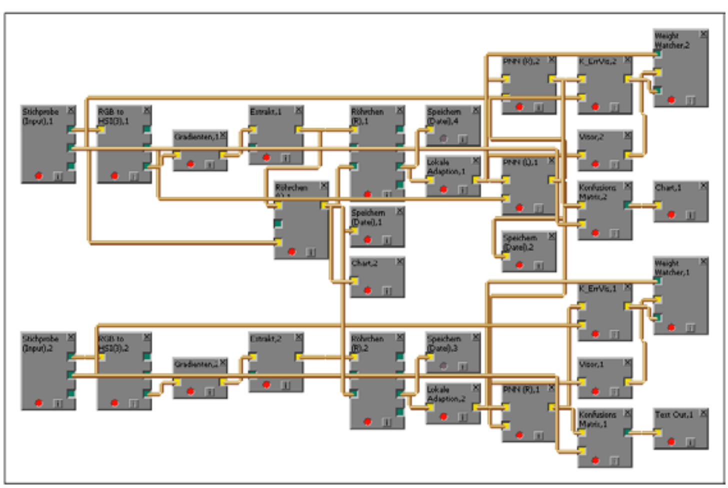


- Medical Laboratory Robot DAVID:
- **Task**: Tubes sorting & decapping
- Multiple installation sites in Europe

- **M**achine-**I**n-the-**L**oop-**L**earning
- General system development
- Instance training for compensation of nonidealities & deviations

Application Examples

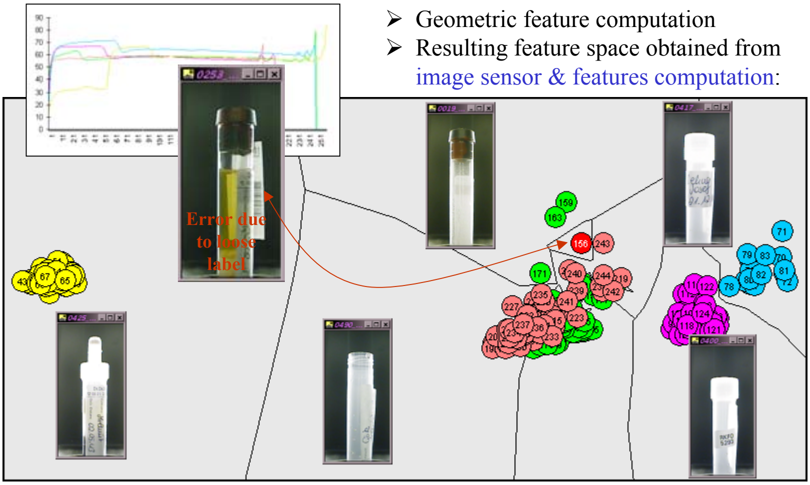
- DAVID generic training system:



Application Examples

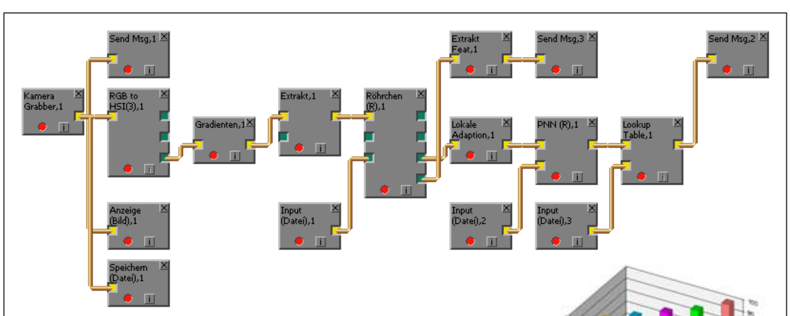
- Feature Space and Classification for Medical Tube Recognition

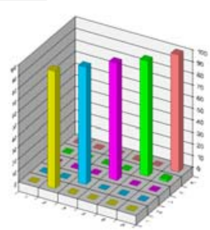
- Geometric feature computation
- Resulting feature space obtained from image sensor & features computation:



Application Examples

- DAVID generic test system:

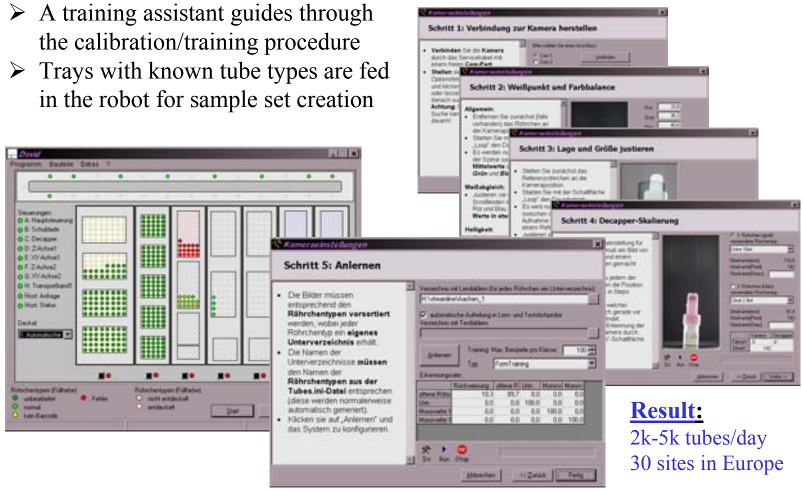




- The generic recognition system performs well
- Site-specific variations affect performance !
- **MILL** concept compensates these deviations
- Training limited to types actually to be recognized !
- *Aging effects can also be compensated by retraining*

Application Examples

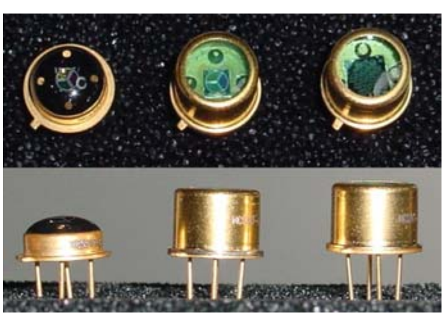
- A training assistant guides through the calibration/training procedure
- Trays with known tube types are fed in the robot for sample set creation



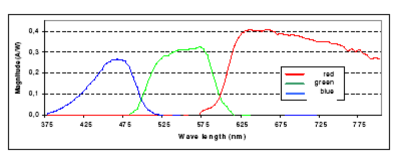
Result:
2k-5k tubes/day
30 sites in Europe

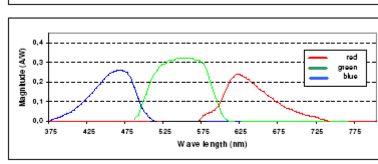
Application Examples

- Wireless color sensor system and its application



MAZeT color sensors in TO5 package, from left to right : MCS3AT, MCS3BT, MCSi

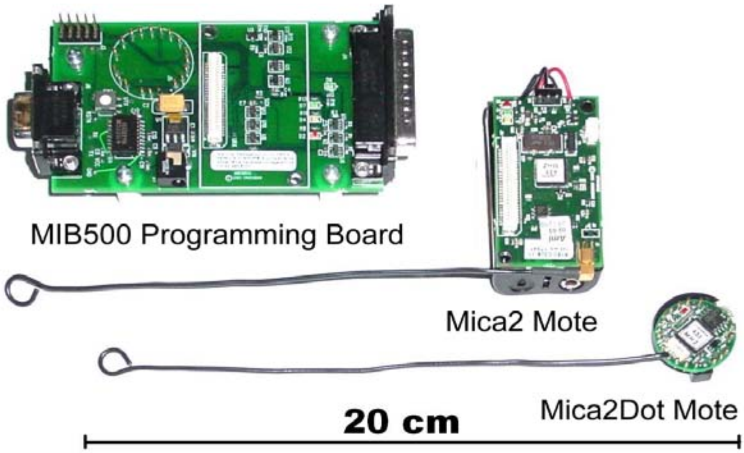




Spectral response curves for MCS3AT (top) and MCS3BT / MCSi (bottom) (© MAZeT Data Sheet MCS3AT/BT)

Application Examples

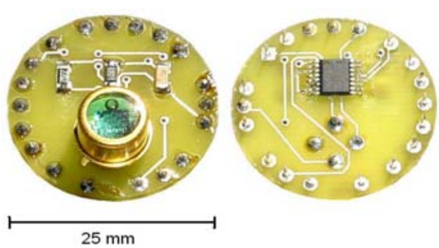
- Xbow Mica2 and Mica2Dot Hardware



Application Examples

- MAZeT color sensors were employed with 4-channel transimpedance amplifier:

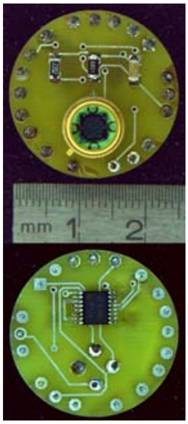
$$U_{out}(I_{in}) = \begin{cases} U_{ref} - I_{in} \cdot R_f & if \quad U_{ref} \geq I_{in} \cdot R_f \\ 0 & else \end{cases} \qquad (1)$$

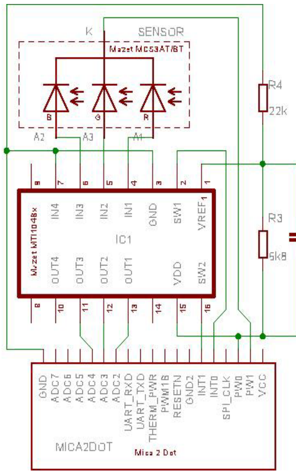


- Extension board to MICA2Dot motes with ATMEL Atmega 128 µC & wireless com. by CHIPCON CC1000 fm-transc.-chip (433 MHz)

Application Examples

- Wireless color sensor system: Schematic and Board





- Photo current to voltage conversion:

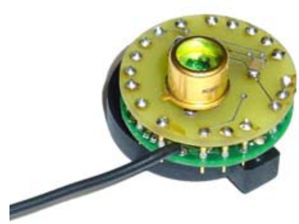
$$U_{ref} = \frac{R_4}{R_3 + R_4} U_{bat} \quad (2)$$

$$U_{out} = \frac{R_4}{R_3 + R_4} U_{batt} - I_{in} R_f \quad (3)$$

$$U_{batt} = 0.6V \cdot \frac{1024}{ADC_{batt}} \quad (4)$$

Application Examples

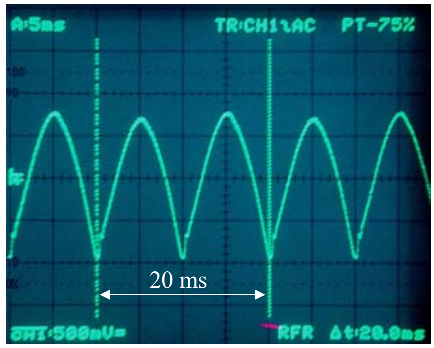
- Wireless color sensor system: Base Station and Color Sensor Module



- Simple SW for sensor readout based on TinyOS and Linux/Cygwin) on PC
- The achieved wireless color sensor module was investigated for color registration & classification
- **Goal:** functional validation & feasibility experiments

Application Examples

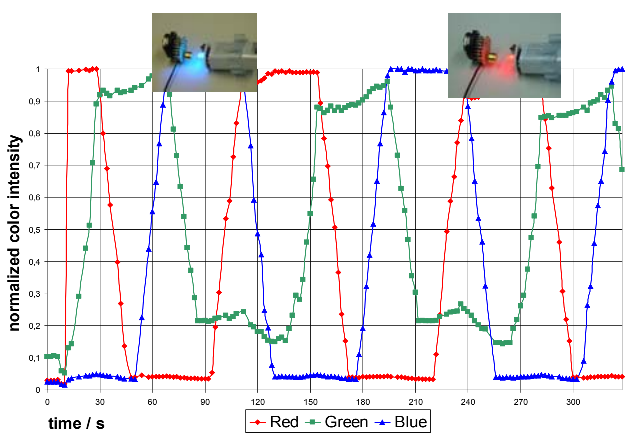
- Functional Validation: Flourescent Lamp Measurement



- Response of Color Sensor to Illumination by a Flourescent Lamp. **Left:** Test Setup, **Right:** Green Channel Amplifier Output

Application Examples

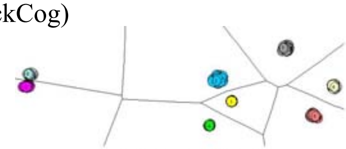
- Functional Validation: Tri-Color-Source Measurement



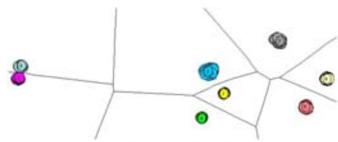
Application Examples

- **Color classification:**
  Paper Strip with Eight Sample Colo

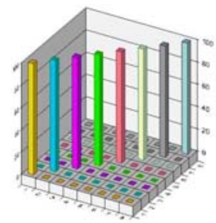
- Two series of 100 repeated measurements for each color (class), were made with the MCS3BT and used in NN-classification (QuickCog)



a) Resubstitution



b) Generalization

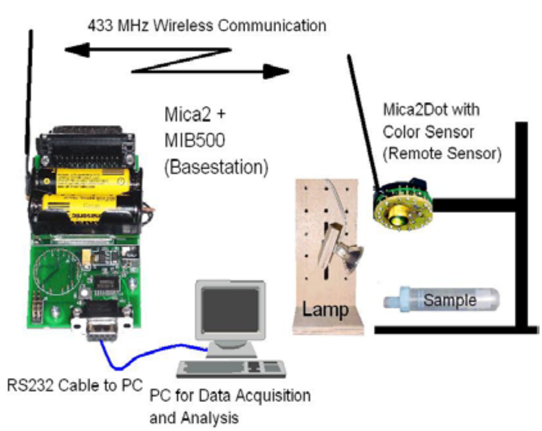


c) Graphical Representation

- Results confirm feasibility of wireless sensor module for classification

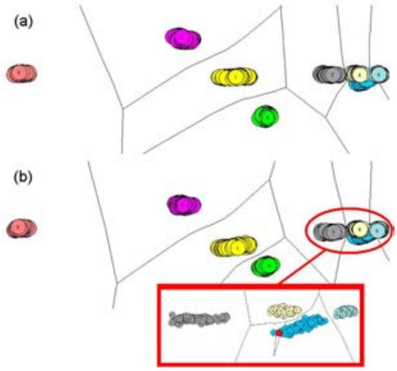
Application Examples

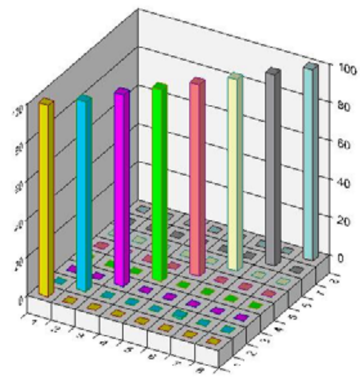
- Alternative tube classification by wireless color sensor module:



Application Examples

- Achieved Medical Tube Classification Rates
- Two series of 100 measurements for each of seven tube types (restricted problem) and an eight uncapped tube were recorded

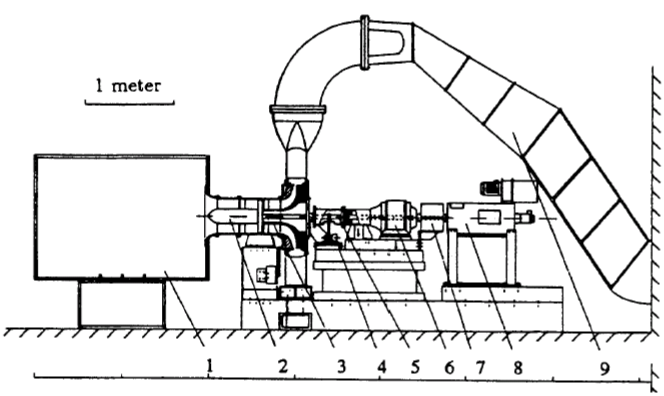




- **Result:** recognition rate of 99.875% (type 6 to type 2 confusion)

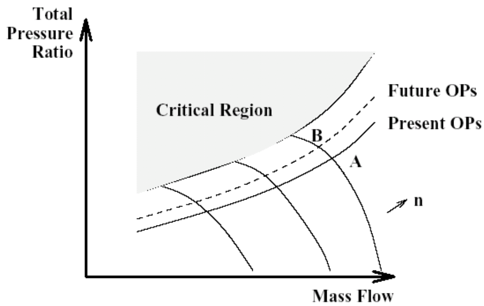
Application Examples

- **Mechatronic Application:** Stall-Margin-Indicator (SMI) for aircraft jet engines (TU Darmstadt, FG Flugantriebe)



Application Examples

Compressor Operation Chart

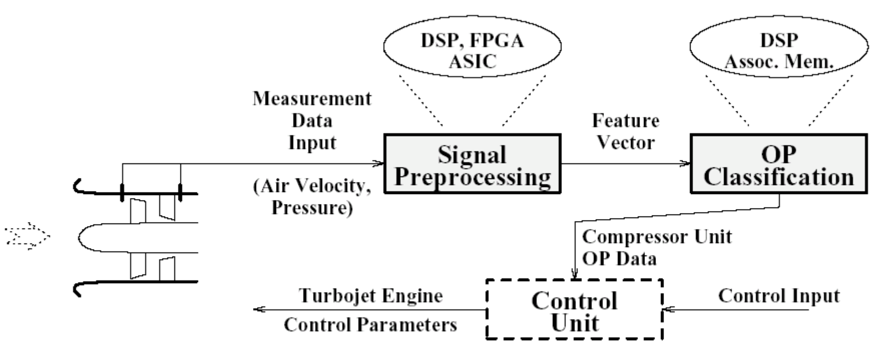


Goal:

* Increase Performance / Weight Ratio by moving the OP towards the Critical Region (A → B)

Application Examples

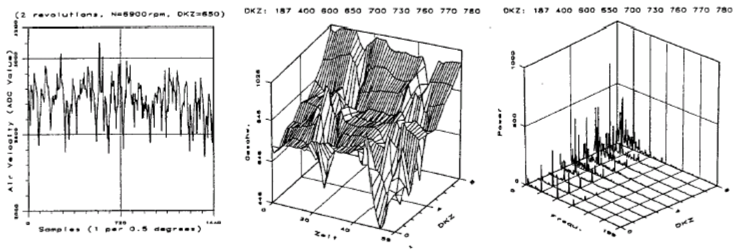
Turbojet Engine Control System



Turbojet Engine Compressor Unit

Application Examples

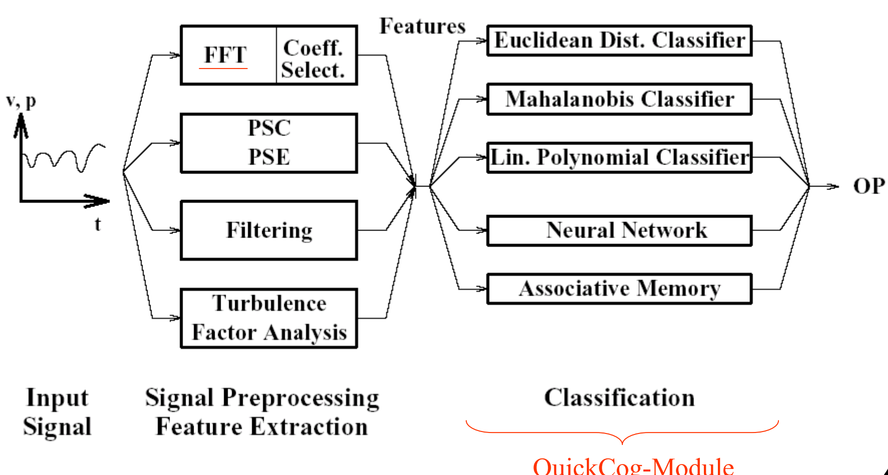
Input Signals from Compressor Unit



Input Signal vs. Time — Air Velocity vs. Time vs. DKZ — Signal Spectra vs. DKZ (1024 pt FFT)

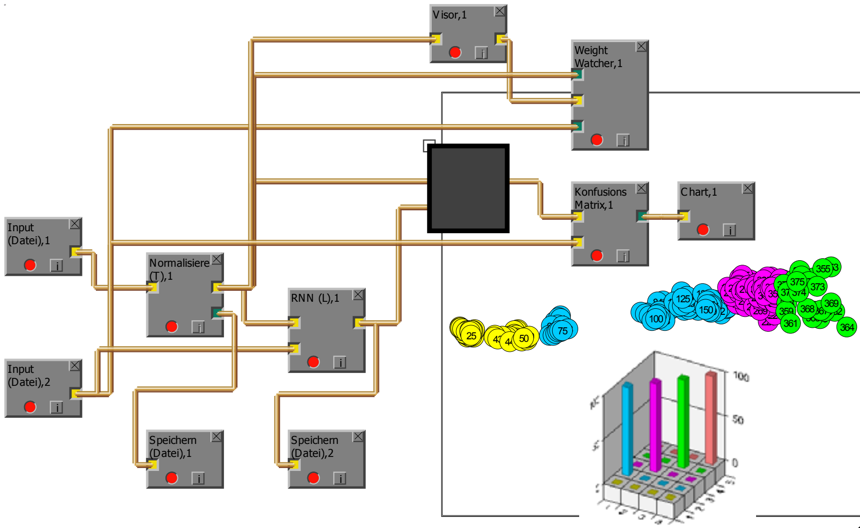
Application Examples

Signal Processing for OP Estimation



Application Examples

- ➢ QuickCog SMI Classification Module:



QuickCog Demonstration

- ➢ Several data sets have been acquired for the SMI task from the described setup
- ➢ They have been archived as classification benchmark data similar to other repository data
- ➢ In QuickCog SMI a training and a test module has been established for the SMI classification problem
- ➢ Feature data from FFT spectra with 24-dimensions, 375 samples, and 4 classes for four operating regions are employed
- ➢ Due to the significant dynamic range, normalization has been applied before classification

- ➢ QuickCog demonstration for the SMI partial system

Main Objectives

- Introduce Master and PhD students to the state-of-the-art of sensory systems and the underlying information processing requirements
- Familiarize with advanced information processing methods for the design of intelligent systems
- Develop the skills to use methods from signal processing, statistics, artificial neural networks, evolutionary computation, fuzzy and hybrid systems to process sensor signals
- Extend these basic skills to systematically combine methods to design and validate a complete sensor signal processing system
- Tackle applications from Mechatronics to Visual Inspection
- Develop the ability to evolve and extend a basic system implementation for modified requirements
- Provide understanding of the interaction of real-world implementations with the chosen algorithmic architecture
- Introduce to adaptation techniques for compensation of (dynamic) interactions and influences (drift, aging, etc.)

Course Contents:

1. Introduction
2. Signal Processing and Analysis
3. Feature Computation
4. Cluster Analysis
5. Dimensionality Reduction Techniques
6. Data Visualization & Analysis
7. Classification Techniques
8. Sensor Fusion
9. Systematic Design of Sensor Systems
10. Outlook

Sensor Signal Processing

Recommended Textbooks and complementary Readings:

1. **R. Hoffmann, *Signalanalyse und Erkennung*, Springer 1998, ISBN 3-540-63443-6**
2. **S. Haykin, *Neural Networks – A Comprehensive Foundation*, Prentice Hall, 1998, ISBN 0132733501**
3. **R. Duda, P. Hart, D. Stork, Pattern Classification, Wiley, 2000, ISBN 0471056693**
4. **K. Fukunaga, Introduction to Statistical Pattern Recognition, Academic Press, 1990, ISBN 0122698517**
5. **H.-R. Tränkler, E. Obermeier (Hrsg.), Sensortechnik – Handbuch für Praxis und Wissenschaft, Springer, 1998**
6. **H. Ahlers (Hrsg.), Multisensorikpraxis, Springer, 1997**
7. **R. Schalkoff, *Digital Image Processing and Computer Vision*, John Wiley & Sons, 1989.**

List will be extended during the course presentation

Sensor Signal Processing

Software for hands-on experience of course contents:

1. **QuickCog: Image Processing and Recognition System Design Environment (Evaluationversion): http://www.eit.uni-kl.de/** Research QuickCog **(Visual Programming of Image Processing and Recognition Systems, Sample-Set oriented Learning)**
2. **Matlab, standard in signal processing and engineering applications, class-room licence in Lab 12/425 available, http://www.mathworks.com**
3. **GNU Octave (free Matlab compatible program) http://www.octave.org**

List will be extended during the course presentation