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Schloss Dagstuhl,
Germany

From Sensors to Context

Summer School on Wireless Sensor Networks and Smart Objects

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Overview

1. Motivation and Introduction
2. Sensors
3. Sensor Output and Connections
4. Power and Sensors
5. Designing a Sensor System
6. Low-level Processing
7. Perceptual Components
8. Matching and Learning
9. Context and Situation

1. Motivation

How to describe a Situation?

It is difficult to describe and detect a situation

- A car is going to have a serious accident
- Two people are undecided what to buy
- Someone is sleeping in a room
- A family having dinner

…but often it is a prerequisite to recognized situations for building intelligent objects.

…and it is even harder to predict a future situation – but we (humans) do it all the time.

How is a situation characterized using sensor value?

Example: Someone is sleeping in a room in a care home

Sensors
- Motion sensor overseeing the room (ON/OFF)
- Weight sensor in each leg of the bed (0-100)
- Light sensor (0-100)
- Door sensor (OPEN/CLOSE)
- Pressure mat in a rag on the floor (ON/OFF)
- Microphone providing noise level (0-100)

Find a function that takes sensor values as input and that tells if someone in sleeping in the room or not

How is a situation characterized using sensor value?

Example: Someone is sleeping in a room in a care home

Issues
- Sensing over time required
- Calibration (at least initially)
- Function is dependent on the sensor setup and the user
- Function is not always correct (exceptions)
- Some sensors don't contribute
- Learning as an option

Even in this simple case it is not trivial to set-up system

Perception in Nature I

- Having **perception** and cognitive functions are the **foundation of intelligent behavior** of creatures.
- **Acting and reacting with respect to the current situation is a basic property of most intelligent systems**.
- Looking at flora and fauna it is a major advantage in the struggle for survival to have the ability of **being adaptive**. The capability to adapt to new circumstance and situations is a vital quality for virtually all living organisms and a major advantage in the struggle for survival.

Perception in Nature II

- Senses in nature cannot be directly compared to sensors in a technical world.
- Senses comprise the whole process from the reception of the stimulus, translation from stimulus to signal, signal transport and the processing on several levels.

- Vision
- Hearing
- Smell
- Taste
- Touch
- Temperature
- Gravity and acceleration
- Position and constellation of (body) parts
- magnetic fields
- Electric fields

Perception in Nature III

- **To understand** or at least interpret information that is sensed from the environment **knowledge** or **experience** (or memory) is **required**.
- Creatures learn during their development how to **assign meaningful and abstract situations to complex stimuli** received by the sensory system. This is based on the presupposition that similar situations are characterised by similar stimuli.
- **Comprehension** of a situation or **understanding** of the implications given by a situation is a further step, which is to a great extent based on the **recall of experience**.

Situation and Context

- **Situation**
  A situation is the state of the real world at a certain moment or during an interval in time at a certain location.
- **Context**
  A Context is identified by a name and includes a description of a type of situation by its characteristic features.
- **Situation S belongs to a Context C**
  A situation S belongs to a context C when all conditions in the description of C evaluate to true in a given situation S.

Context Recognition

- **It is assumed that for all situations that belong to the same context the sensory input of the characterizing features is similar.**
- Creating a description of a context includes similar problems to creating a query for information retrieval. To assess the quality of a description measures such a *precision* and *recall*, well known from information retrieval.
- Based on these definitions context can be regarded as a pattern, which can be used to match situations of the same type.

Warning at the beginning There are limitations…

"The physical world is a partially observable dynamic system ..."

"... sensors are physical devices have inherent accuracy and precision limitations"

2. Sensors

What is a Sensor?

- A sensor is a technological device or biological organ that detects, or senses, a signal or physical condition and chemical compounds.
- A electronic, electrical, micro-mechanic or electro-mechanical device that responds to a stimulus, such as heat, light, or pressure, and generates a signal that can be measured or interpreted.
- A function of time that returns a value (binary, number, vector, array) dependent on a measured parameter.

Some "classical" Sensors

- light sensors: photocells, phototransistors, CCDs,..
- sound sensors: microphones, seismic sensors…
- temperature sensors: thermometers, thermocouples, thermistors, …
- radiation sensors: Geiger counter, dosimeter
- electrical resistance sensors
- electrical current sensors
- electrical voltage sensors
- electrical power sensors
- magnetism sensors: magnetic compass, Hall effect device, …
- pressure sensors: barometer, pressure gauge, …
- gas and liquid flow sensors
- chemical sensors: pH glass electrodes, lambda sensors, …
- motion sensors: speedometer, tachometer, …
- orientation sensors: gyroscope accelerometer, …
- mechanical sensors: switch, strain gauge, …
- proximity sensor
- …

See http://en.wikipedia.org/wiki/Sensor

Information "Sensors"

- Sensors that are related to the device or system Examples
  - battery voltage,
  - RSSI,
  - real-time,
  - current packet loss,
  - current power consumption
  - location sensors
  - devices in vicinity
- Access to information over a network (e.g. WWW)
  - weather in New York
  - share price of GOOGLE

Bio-Sensors

- Sensors to measure physiological parameters in humans and animals
- Towards sensing emotions…

- Example
  - Galvanic skin response
  - Heard rate
  - Blood pressure
  - Blood oxygen saturation
  - EEG, ECG
  - …

Image from http://affect.media.mit.edu/

What can you measure? Some Examples

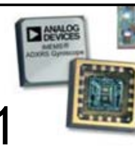
- Temperature Sensor
  - weather / temperature
  - human proximity and touch
  - device in operation
  - indoor / outdoor?
  - speed?
  - …

- Light Sensor
  - light level
  - light frequency (50Hz/60Hz)
  - indoor / outdoor?
  - movement?
  - usage of a environment
  - touch
  - …

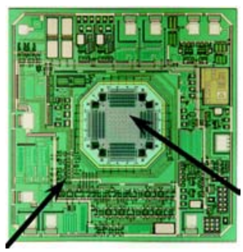
- Accelerometer
  - tilt
  - vibration
  - acceleration
  - gestures
  - shock
  - position?
  - Interaction?
  - …

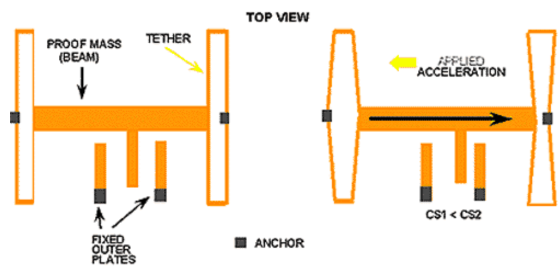
Dependent on the application a sensor can be used to measure different phenomena in the real world

Sensor in Detail
Analog Devices Accelerometer 1



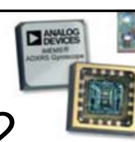
- iMEMS
  integrate micro electrical mechanical systems
- Everything is integrated on a chip
  - mechanics and circuits!

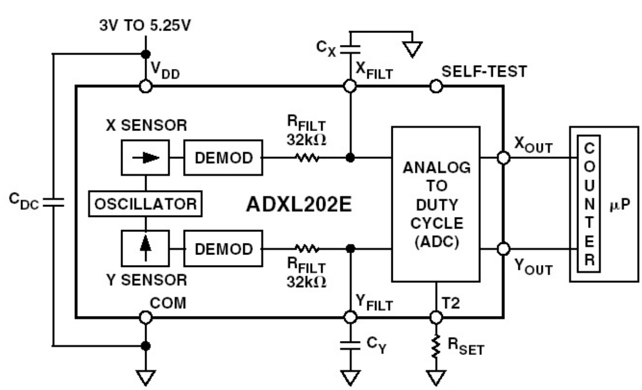


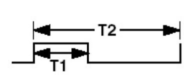


From www.analog.com

Sensor in Detail:
Analog Devices Accelerometer 2





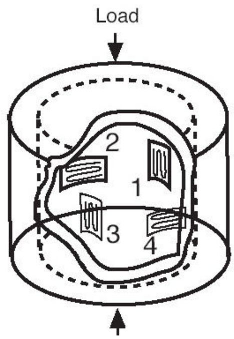


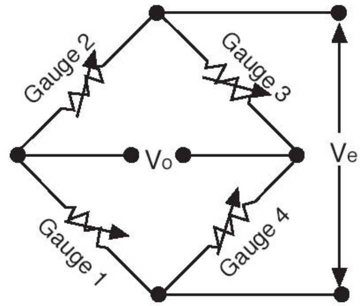
From Analog Devices, ADXL202
Read the datasheet …

$A(g) = (T1/T2 – 0.5)/12.5\%$
$0g = 50\%$ DUTY CYCLE
$T2 = R_{SET}/125M\Omega$

Sensor in Detail:
Load cell

Compressive load transducer

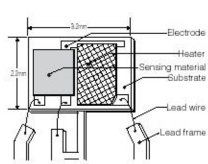


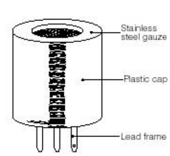


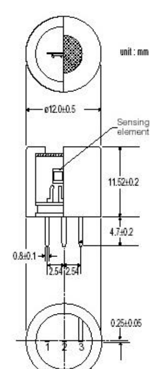
- Analog Output
- Stain Gauges measure change in length
- From RS Components Datasheet 232-5957

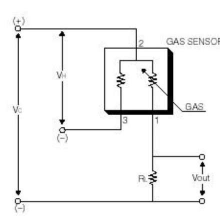
Sensor in Detail:
Gas Sensor 1

Model	**TGS 21XX**
Element type	**S1**
Package type	**Plastic**









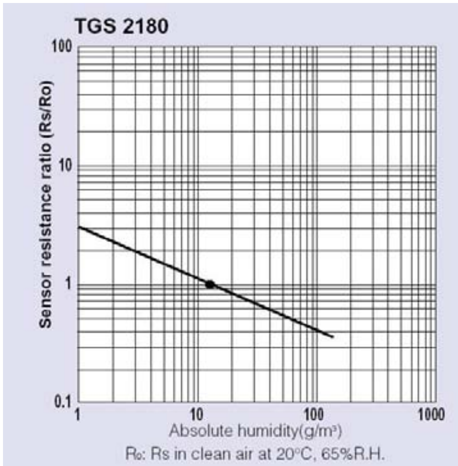
Configuration : -Single sided, 1 element
Features : -Simple structure
Benefits : -Suitable for large volume and low cost applications

Pin connection
1 : Sensor electrode(−)
2 : Common(+)
3 : Heater(−)

Circuit conditions
V_C: 5V±0.2V DC
V_H: 5V±0.2V DC
R_L: Variable($P_S \leq$15mW)

From: Frigaro Gas Sensors Series 2000

Sensor in Detail: Gas Sensor 2



From: Frigaro Gas Sensors Series 2000

Problems with Sensors

- Need for calibration
- Sensors are Inaccurate (within a given specification)
- Sensors are unreliable (within a given specification)
- Noise and false readings are common
- Timing between processor and sensor is often critical

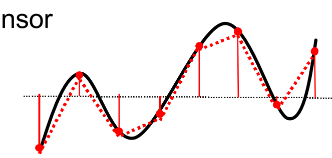
- Mechanical Issues, casing
  “Sensor may need a hole to see the world”

3. Sensor Output and Connections

Acquiring Sensor Data

- In many case “Analog” phenomena are sensed
- Analog to digital conversion (ADC) is required
- Sampling rate as a central parameter that describes how often digital samples are taken from the analog signal
- ADC in the sensor, as extra component, or in MCU

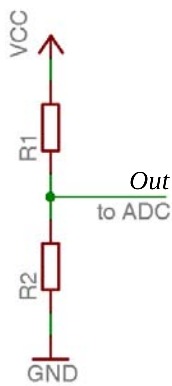
- Issues for selecting the sampling rate
  - Speed of change of the parameter in the world
    for reconstruction of the frequency f we need at least 2f (Nyquist)
  - Speed of change supported by the sensor
  - Capabilities of the ADC
  - Power consideration (energy saving)



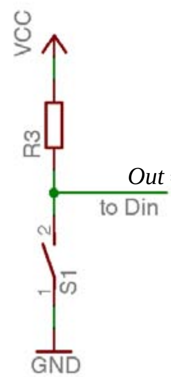
Basic Electronics
(do you remember from High school?)

- Voltage division
- Resistor may be a sensor

- Pull-up resistor
- Input is in a defined state

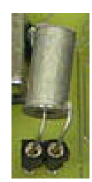


$$Out = \frac{R_2}{R_1 + R_2} VCC$$

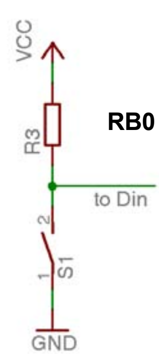


$$Out = \begin{cases} VCC & if \quad S1 \quad opened \\ GND & if \quad S1 \quad closed \end{cases}$$

Digital Output



- Sensors with binary state e.g. on/off
- Typical sensors
  - Push button
  - Switch
  - Ball switch
- Output after threshold component (Schmitt-trigger) of a analog sensor
- To acquire read digital input pin



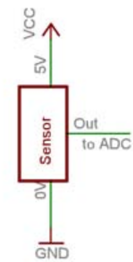
- Repeat … as long as S1 is pressed
```
while( !input(pin_B0)) { ... }
```

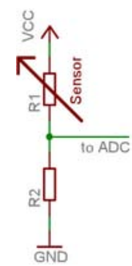
Analog Output

- Sensor with a analog output, e.g. IR distance sensor, PIR
- Sensors as variable resistor e.g. LDR, Pressure sensor, PTC

- To aqcuire read analog port

```
setup_adc(ALL_ANALOG);
set_adc_channel(0);
value=Read_ADC();
```



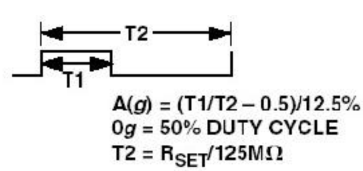


Pulse Width Modulation (PWM) Duty-Cycle

- Simple digital interface to communicate a number
- A value is code using the timing in a digital output
- Reading a digital line and measure the time
- Examples: Accelerometer, sensor modules
- Acquire using a digital in counting time for high and low

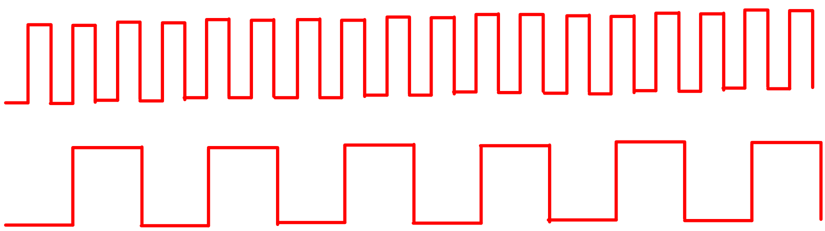
```
wait till B0 is high
counter=0
start counter
wait till B0 is low
T1=counter
wait till B0 is high
T2=counter
```

ADXL202



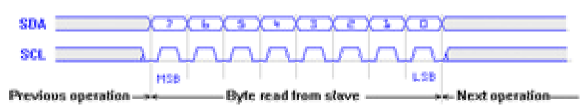
Frequency Output

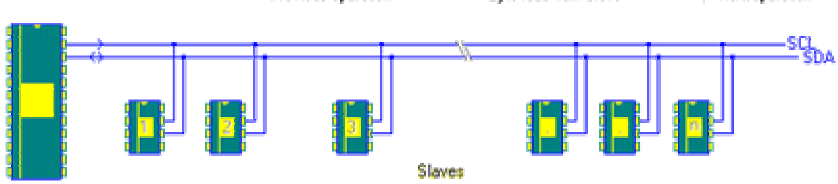
- The output frequency is used to communicate the sensor value
- Similar to PWM
- Use a counter to read frequency



I2C bidirectional Communication

- Bus topology
- Master-Slave protocol
- Usually MCU is master and sensor(s) slave
- Electrical Connection
  - SDA (Data)
  - SLC (Clock)
  - GND
- Devices
  - Different sensors
  - external memory
  - further components
- Read/write primitives

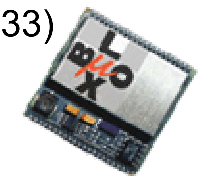




http://www.esacademy.com/faq/i2c/

Serial Line (TTL, RS232)

- Protocol from the “terminal world” ;-)
- Commonly used to interface to more complex sensors
- Minimal electrical connection
  - (TXD)
  - RXD
  - GND
- For 12V is a driver required (e.g. MAX233)
- Typical Examples
  - GPS
  - RFID Reader
  - Connecting sensor or receiver to a PC



Many More… Communication with Smart Sensors

- 1-Wire Bus, data and power over one line
  E.g. I-Button, Temperature Sensor
- SPI digital output (and input)
  Serial digital interface
- RS485, RS422 serial bus for longer distances wired communication
- IEEE1451, protocol for smart sensors
- …

- Often depends on the sensors used and general requirements in the projects.

4. Power and Sensors

Minimizing Power Consumption Generate Power form Sensors

- Use sensor to wake up a processor
- Use sensors that generate power
- Build circuits that generate an interrupt on change of sensor values

- Example
  - Solar cell as light sensor with no power
  - Piezoelectric Element

- Search for *Parasitic Power Harvesting*
- Energy Scavenging for Mobile and Wireless Electronics, Paradiso, J.A. and Starner, T., IEEE Pervasive Computing, Vol. 4, No. 1, February 2005, pp. 18-27.

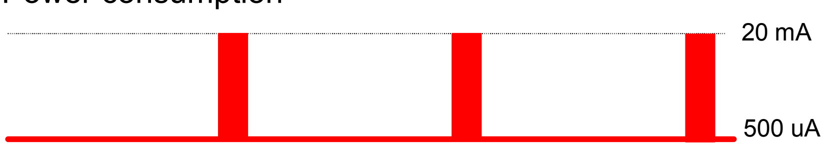
Minimizing On-Time

- Use clever sampling strategies
  - switch the whole system (including sensors) off between sensor readings
  - sample at low speed in general
  - Increase speed when something interesting happens
- Example – detect gesture interaction
  - Switch of the system for a time that is acceptable as delay for recognition (e.g. 250 ms)
  - Switch system on, power sensor read a sample and compare to previous values (e.g. will take 5ms)
  - Only go into fast sampling mode if there is change
  - Results in much lower energy consumption (e.g. 2%)

Example
Check every 250ms for a change

```
while(TRUE) {
  power_down_ms(250);
  power_sensor(SENSOR_1);
  x=read_sensor(SENSOR_1);
  if (diff(x,xold) > THRESHOLD) { recognizer(); }
  else { xold=x; }
}
```

Power consumption

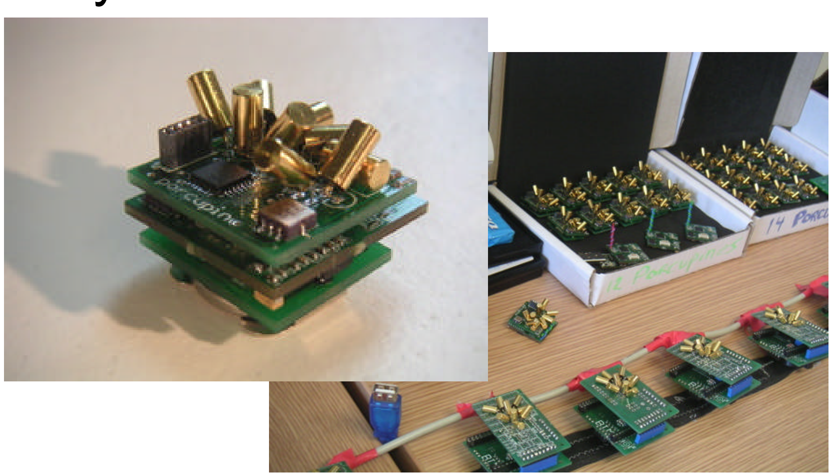


Sensor Hierarchies
Variable Processing Power

- Use a low-power (or no-power or energy harvesting) sensor to monitor
- Power the sensor with high power consumption only when a change is expected/predicted

- Example: Porcupine
  - Ball switches monitor change at low processing speed with minimal power consumption
  - In case of change accelerometers are powered and processing speed is increased
  - Kristof van Laerhoven, http://www.comp.lancs.ac.uk/~kristof/research/notes/porcupine/

Example Porcupine
Body Sensor Network



From: http://www.comp.lancs.ac.uk/~kristof/research/notes/porcupine/

5. Designing A Sensor System

Requirements on Sensing in a Ubiquitous Computing Environment

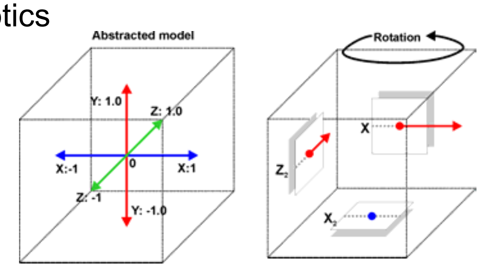
- Design and Usability
- Energy Consumption
- Calibration
- Start-up Time
- Robustness and Reliability
- Portability, Size and Weight
- Unobtrusiveness, Social Acceptance and User Concern
- Price and Introduced Cost
- Precision and Openness

A. Schmidt, and K. Van Laerhoven, *How to Build Smart Appliances*?, IEEE Personal Communications 8(4), August 2001
http://www.comp.lancs.ac.uk/~albrecht/pubs/pdf/schmidt_ieee_pc_08-2001.pdf

Arranging Sensors

- The position of sensors on a object or in the environment matters!
- Dependent on the position different phenomena will/can be measured
- The sensor in the “right” position can save processing and energy
- Embodiment – see robotics

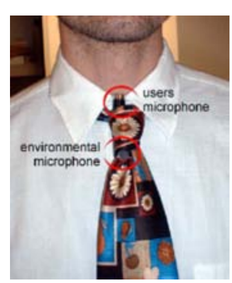
- Example: placement of acceleration sensors in a interactive cube



Multiple Sensors

- Multiple sensors (of the same type) can ease recognition of certain phenomena
- Correlation of sensor readings
- Networked sensors and time stamped readings

- Example: detect the number of sound sources
  - very difficult with one microphone
  - much simpler with multiple distributed microphones



Sensing Options and Context Use

- Sensing
  - Observation from the outside (extrinsic)
  - Sensing from within (intrinsic)
  - combined
- Context used by
  - Entity
  - Observer
  - Anyone

	Context user		
	Entity	*Observer*	*Anyone*
Intrinsic	No communication	communication	communication
Extrinsic	Communication	No communication	communication
combined	communication	communication	communication

6. Low level Processing

Buffering Data, Histories

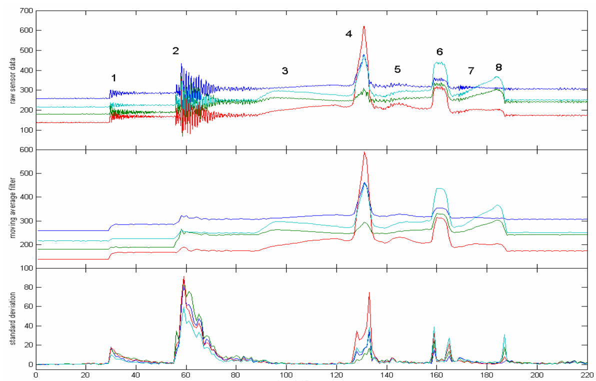
- Motivation
  detect a conversation from audio?
  - Not possible with a snapshoot
  - History is required
- In many cases sensor readings need to be considered over time to get meaningful information
- Sensor data is buffered (e.g. the last 50 values)
- Processing of sensor data from the buffer
- Issues
  - Size of buffer
  - Time stamp vs. samples at fixed intervals
  - Appropriate methods and algorithms for processing

Basic Statistics

- Motivation
  - data gathered is not perfect (e.g. outliers, faulty readings)
  - Features (e.g. change, average) are of interest rather than a single value
- Basic statistics are in many cases computationally cheap
- Can help to reduce effort for calibration
- Typical Features
  - average, median,
  - range, interquartile range,
  - variance, standard deviation
- Change of sensor values vs. absolute values

Filtering Sensor Readings

- Can be implemented in hardware or software
- Dealing with noisy data
- moving average
- low-pass filter
- Many more …



Time domain and Frequency domain

- Sensor values are sample in discrete time steps
- Often changes are of central interest (e.g. “it is getting colder”)

- Analyzing over time
  – derivatives, 2nd (higher) derivatives
  – summing up sensor values over time, integration
  – Summing up difference between sensor values
- Transformation into Frequency domain
  – Counting zero crossings to get base frequency
  – FFT

Feature Extraction

- Features over a given time interval are calculated
- Features are characteristic for a context
- Features are used in higher level processing and for recognition

- Example
  - Audio signal of 4 microphones over 30 seconds
  - Possible Features (depend on contexts to recognize):
    - average audio level, variance of audio level
    - correlation between microphones
    - distribution of audio levels, number of distinct sound sources
    - frequency spectrum for 2 second periods

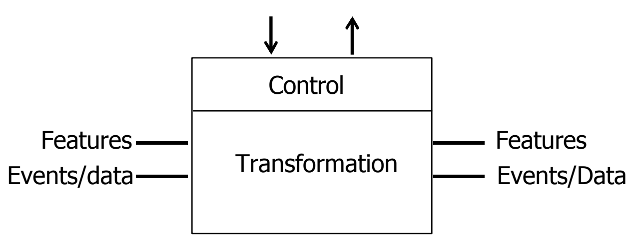
7. Perceptual Components

Sensing and Perception

- Bridging the gap between sensors and applications
- Sensors observe physical phenomena in real the world
- Applications use (implicit or explicit) world models
- Perception: associating sensor observations with meaning

- The world is represented as a set of collection of sensor reading
  - Numeric, symbolic or streams of data
  - Can be considered as observable variables
  - May contain meta data (e.g. time, location, confidence)

Perception Model
Basic Perception Component

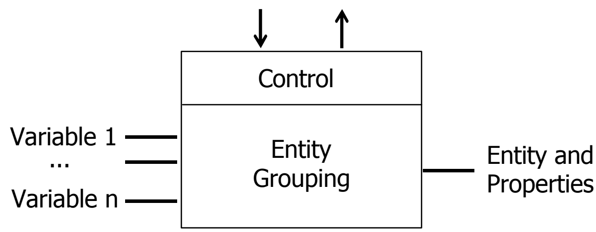


- Transforming observed features/events/data to “higher level” features/events/data
- Transformation can be controlled by the system or by context
- Perception as multi-step process

See Crowley et al., "*Perceptual Components for Context Aware Computing*", UbiComp 2002, Springer LNCS 2498

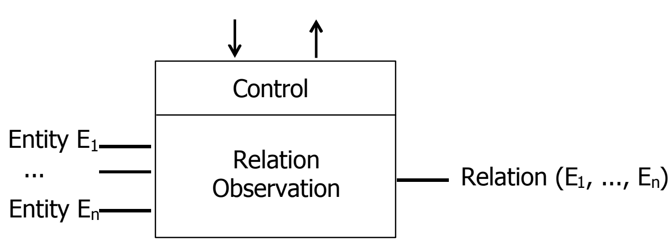
Associating observations with entities

- grouping of observations
- entity corresponds to a physical object
- easy if sensors are directly associated with an object
- hard if sensors are external



Detecting relations Grouping

- Determining relations between entities
- Easier with sensors external to the entities
- Harder with embedded sensors



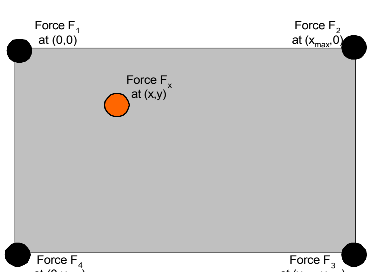
Example: A Context-aware Table

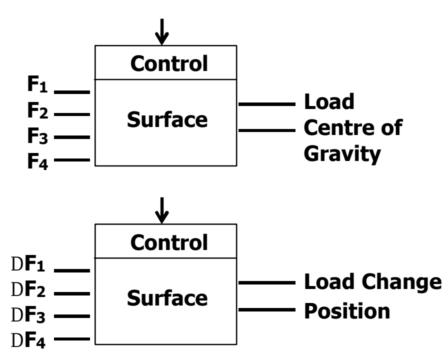
- Idea: augment a table to be context-aware
  - Instrument with sensors to detect activity on the table surface
  - Use perception techniques to extract context
  - Use context information to support different applications

- What we might want to detect
  - Placement and removal of things on the table
  - Movement on the table surface
  - Identity of objects on the table

Sensor system for the table

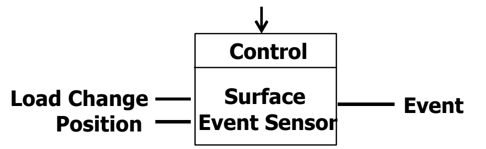
- Load cell in each corner
- Measuring forces
- Trade-offs:
  - Accuracy
  - Speed, Sampling rate
  - Maximal load



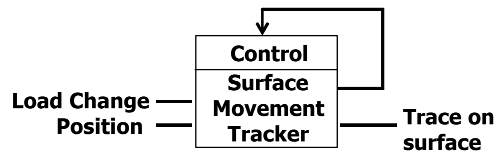


Higher level Perception

- Basic event detection
  - Change in load at x,y
  - Increase in load by w: an object of weight w has been placed at x,y
  - Reduction in load: object removed from x,y



- Detecting movements
  - Track change in load distribution on surface
  - Continuous change is associated with movement



8. Matching and Learning

Rule based approach

- A (fixed) set of rules that specify a context
- Explicit definition of context parameters (features) to match a context
- In many application scenarios this is very simple to implement
- It is easy for small number of features and contexts that are well understood

- Example mobile phone
  - `in_hand := (touch==TRUE) && (acceleration > EPSILON);`
  - `in_suitcase := (touch==FALSE) && (light == DARK)`
  - `...`

Off-line learning
Supervised training

- The context is learned by “experience”
- Data examples for a context is learned base on sensor data or feature
- The training data is collected in typical situations that belong to a context
- In a new situation the received stimulus (sensor data / features) are compared to the data learned
- Different algorithms, e.g.
  - Statistics
  - Nearest Neighbor matching
  - Backpropagation Neural Networks
- Useful for contexts that do not change but where the relation between sensor values and situation is not easily understood

On-line/Continuous learning unsupervised learning

- sensor data or features are continuously used to learn a context
- clustering data and labeling clusters
- useful for changing environments
- various methods, e.g. Self Organizing Map

- Simple example – User's favorite place
  - Base station ID as feature
  - Measure every minute the ID
  - "learn" the user favorite place
  - This relates to a time frame (e.g. favorite place over the last month)

Learning and adaptation

Concept of Learning/ adaptation	*Usage*	*Algorithms*	*examples*
No learning, fixed	Contexts are globally valid	Design time data analysis	Static Rule based systems, Preset Supervised NN
Learning phase	Contexts are stable but different depending on the use case	Training and/or data analysis capabilities built in	Dynamic Rule based systems Supervised Neural nets
Fully adaptive, always learning	Contexts are changing over time	Adaptive algorithms	SOM, ISL

9. Context and Situation

Modeling Context

- Modeling the domain
- Alternative approaches
  - Top-down
    Situation → Context → Features → Sensors
  - Bottom-up
    Sensors → Features → Context → Situation

- Do not try to model the world…
  …model your applications world!

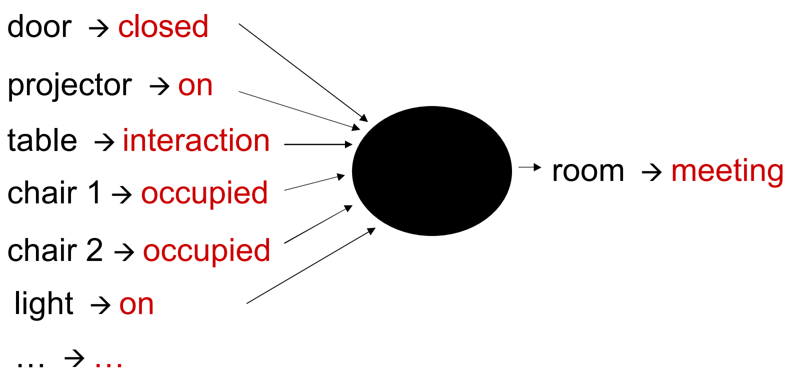
Bottom-up Context Models

- Context is anchored in artifacts
  - Modeling and acquiring context on entity level
  - More general properties
  - Flexible, extensible, and simple model
  - Exploiting domain knowledge
- Augmenting artifacts with
  - Sensing
  - Processing
  - Communication
- Context related to interaction with the artifact
  - Combining context on a higher level
  - Time & space correlation

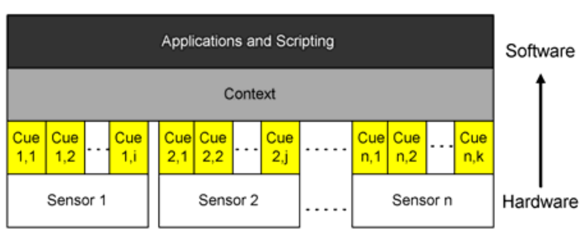
Bottom-up Context - Example

- sofa
  - free
  - occupied with one person
  - occupied with two people
  - occupied with three people
- door
  - open
  - closed
  - degree of openness
  - interaction
- briefcase
  - empty
  - loaded
  - open
  - closed
  - interaction
- sofa (over the top)
  - …
  - jumping on the sofa
  - motion of people on the sofa
  - temperature on the sofa
  - pouring orange juice on the sofa
  - pouring wine on the sofa
  - pouring milk on the sofa
  - cleaning the sofa
  - moving the sofa
  - sofa placed on the stairs
  - sofa upright
  - upside down
  - sofa flying in midair
  - …

Higher Level Context - Example
Time & Space correlation



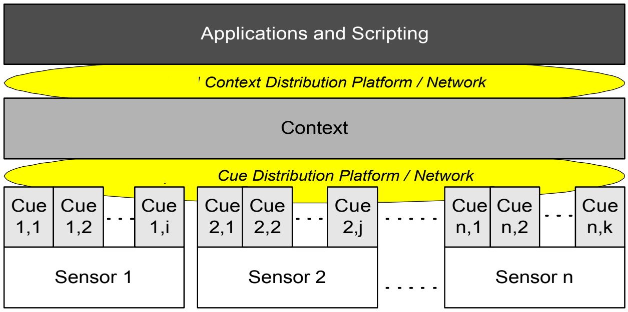
Layered Model for Sensor based Context Awareness



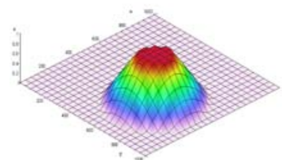
- Application primitives

```
if enter(v, p, n)
   then action(i)

if leave(v, p, n)
   then action(i)

if in(v, p, m) then
   perform action(i)
```

Distributed Model for Sensor based Context Awareness



- Relevance of context information is related to physical distance



Summary

- Sensor provide means to see the real world
- Many different sensors and technologies are out there → read the datasheet
- Power saving and sensor system design are closely related
- Make abstraction/processing into components
- A leveled approach to derive concepts and contexts from sensor
- Learning is a key for many applications

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