Intelligent and Cognitive Sensor Systems

Mark McDermott

With many thanks to *Ricardo Gutierrez-Osuna,* TAMU

Agenda

- Trends
- Definitions
- Overview of Basic Sensors
- Instrumentation
- Intelligent Sensors
- Communications

Trends in Sensor Systems

Trend	Outcome	Solution
Large number of specialized sensors in dense networks	Increase in sensor data - overloading of computational and networking capabilities.	Data reduction and compression
Required increase in reliability and robustness of sensor data	Duplication of sensors	Localized analysis of data and compensation
Requirements to handle multi-modal data	Increase in sensor data	Localized fusing and pre-processing of data
Energy aware design	Use of alternative energy sources	Data-driven computation and energy sensitive algorithms, low-power circuit design.
Use of sensor platforms	Efficient reuse	Specify at highest level of abstraction possible

Sensor Platforms

- RSC WINS & Hidra
- Sensoria WINS
- UCLA's iBadge
- UCLA's Medusa MK-II
- Berkeley's Motes
- Berkeley Piconodes
- MIT's μAMPs

Each one covers different points in (cost, power, functionality, form factor) space….

Question to be asked: Can a single platform cover multiple points?

Systematic requirements of a Sensor Platform

- **The systematic requirements of a sensor platform include:**
  - Accuracy: Provide the ability to compensate for systematic errors, system drift and random errors produced by system parametric changes such as sensor aging, battery aging.
  - Adaptability: Provide the ability to optimize the measuring and processing operations, as well as enable the sensor to adequately respond to changing environmental conditions.
  - Data fusion: Provide techniques to combine information from multiple sensors and sensor types and to ensure that only the most relevant information is transmitted.
  - Robustness & Reliability: Provide the ability to detect corrupted data, self-testing of network path connections and sensor operation, as well as calibration of sensor drift.
  - Information processing: Provide adaptive techniques to improve the efficiency of the data processing and transmission.

What is a Cognitive Sensor Platform?

- **The hierarchy of capabilities of a cognitive sensor platform include:**
  - Self-knowledge - the sensor identifies its purpose and understands its operational functions.
  - Communication - the sensor is capable of transmitting/receiving processed information to/from other devices.
  - Perception - the sensor has the ability to recognize, interpret, and understand sensor data.
  - Reasoning - the sensor is capable of making decisions based on perception of sensor data.
  - Cognition - the sensor is able to use the knowledge, perception, reasoning for advance processing and communication of the sensor data.

Sensor Systems Definitions

- **System**
  - A combination of two or more elements, subsystems and parts necessary to carry out one or more functions
  - To interact with the real world, a system requires
    - Sensors: inputs devices
    - Actuators: output devices
    - Processing: signals, information and knowledge
- **Sensor**
  - A device that receives and responds to a stimulus [Fdn97]
    - Stimulus: mechanical, thermal, magnetic, electric, optical, chemical…
    - Response: an electrical signal (in most cases)
- **Intelligence**
  - The ability to combine
    - A priori knowledge (available before experience) and
    - Adaptive learning (from experience)

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Sensor Systems Definitions (cont)

- **Additional definitions from various sources**
  - A sensor that is capable of modifying its internal behavior to optimize the collection of data from the external world [Whi97]
    - The concepts of adaptation and compensation are central to the Intelligent Sensor philosophy
  - A device that combines a sensing element and a signal processor on a single integrated circuit [PY95a]
    - The minimum requirements of the signal processor are not clear [PY95b]
      - Basic integrated electronics (signal conditioning, ADC)
      - A micro-processor
      - Logic functions and decision making
  - A smart sensor is a sensor that provides functions beyond those necessary for generating a correct representation of a sensed or controlled quantity (IEEE 1451.2) [Fnk00]
    - This function typically simplifies the integration of the transducer into applications in a networked environment

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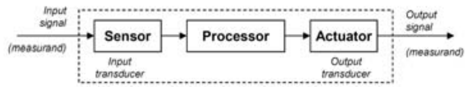
Overview of Basic Sensors

Transducers: sensors and actuators

- **Transducer**
  - A device that converts a signal from one physical form to a corresponding signal having a different physical form
    - Physical form: mechanical, thermal, magnetic, electric, optical, chemical…
  - Transducers are ENERGY CONVERTERS or MODIFIERS
- **Sensor**
  - A device that receives and responds to a signal or stimulus
    - This is a broader concept that includes the extension of our perception capabilities to acquire information about physical quantities
- **Transducers: sensors and actuators**
  - Sensor: an input transducer (i.e., a microphone, thermistor)
  - Actuator: an output transducer (i.e., a loudspeaker, relay)



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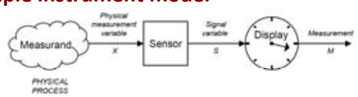
Measurements

- **A simple instrument model**



  - A observable variable X is obtained from the measurand
    - X is related to the measurand in some KNOWN way (i.e., measuring mass)
  - The sensor generates a signal variable that can be manipulated:
    - Processed, transmitted or displayed
  - In the example above the signal is passed to a display, where a measurement can be taken
- **Measurement**
  - The process of comparing an unknown quantity with a standard of the same quantity (measuring length) or standards of two or more related quantities (measuring velocity)

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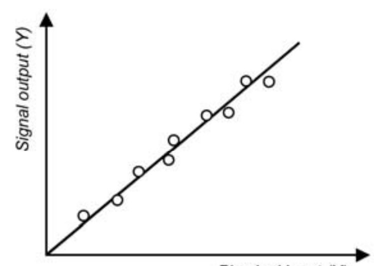
Calibration

- **The relationship between the physical measurement variable (X) and the signal variable (S)**
  - A sensor or instrument is calibrated by applying a number of KNOWN physical inputs and recording the response of the system



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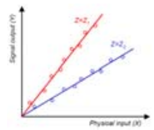
Additional Inputs

- **Interfering inputs (Y)**
  - Those that the sensor to respond as the linear superposition with the measurand variable X
    - Linear superposition assumption: S(aX+bY)=aS(X)+bS(Y)

- **Modifying inputs (Z)**
  - Those that change the behavior of the sensor and, hence, the calibration curve
  - Temperature is a typical modifying input



Sensor characteristics

- **Static characteristics**
  - The properties of the system after all transient effects have settled to their final or steady state
    - Accuracy
    - Discrimination
    - Precision
    - Errors
    - Drift
    - Range
    - Sensitivity
    - Linearity
    - Hysteresis
- **Dynamic characteristics**
  - The properties of the system transient response to an input
    - Zero order systems
    - First order systems
    - Second order systems

Accuracy, discrimination and precision

- **Accuracy is the capacity of a measuring instrument to give RESULTS close to the TRUE VALUE of the measured quantity**
  - Accuracy is related to the bias of a set of measurements
  - (IN)Accuracy is measured by the absolute and relative errors

$$\text{ABSOLUTE ERROR} = \text{RESULT} - \text{TRUE VALUE}$$

$$\text{RELATIVE ERROR} = \frac{\text{ABSOLUTE ERROR}}{\text{TRUE VALUE}}$$

- **Discrimination is the minimal change of the input necessary to produce a detectable change at the output**
  - Discrimination is also known as RESOLUTION
  - When the increment is from zero, it is called THRESHOLD

Precision

- **The capacity of a measuring instrument to give the same reading when repetitively measuring the same quantity under the same prescribed conditions**
  - Precision implies agreement between successive readings, NOT closeness to the true value
    - Precision is related to the variance of a set of measurements
  - Precision is a necessary but not sufficient condition for accuracy
- **Two terms closely related to precision**
  - Repeatability
    - The precision of a set of measurements taken over a short time interval
  - Reproducibility
    - The precision of a set of measurements BUT
      - Taken over a long time interval or
      - Performed by different operators or
      - with different instruments or
      - in different laboratories

Accuracy and errors

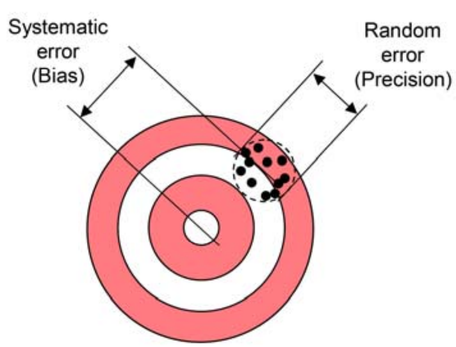
- **Systematic errors**
  - Result from a variety of factors
    - Interfering or modifying variables (i.e., temperature)
    - Drift (i.e., changes in chemical structure or mechanical stresses)
    - The measurement process changes the measurand (i.e., loading errors)
    - The transmission process changes the signal (i.e., attenuation)
    - Human observers (i.e., parallax errors)

Systematic errors can be corrected with COMPENSATION methods (i.e., feedback, filtering)

Accuracy and errors (cont)

- **Random errors**
  - Also called NOISE: a signal that carries no information
  - True random errors (white noise) follow a Gaussian distribution
  - Sources of randomness:
    - Repeatability of the measurand itself (i.e., height of a rough surface)
    - Environmental noise (i.e., background noise picked by a microphone)
    - Transmission noise (i.e., 60Hz hum)
- **Signal to noise ratio (SNR) should be >>1**
    - With knowledge of the signal characteristics it may be possible to interpret a signal with a low SNR (i.e., understanding speech in a loud environment)

Example: systematic and random errors

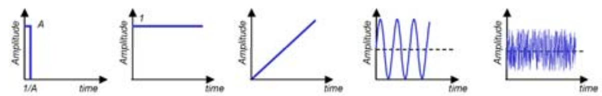


Static Characteristics

- **Input range**
  - The maximum and minimum value of the physical variable that can be measured (i.e., -40F/100F in a thermometer)
  - Output range can be defined similarly
- **Sensitivity**
  - The slope of the calibration curve y=f(x)
    - An ideal sensor will have a large and constant sensitivity
  - Sensitivity-related errors: saturation and "dead-bands"
- **Linearity**
  - The closeness of the calibration curve to a specified straight line (i.e., theoretical behavior, least-squares fit)
- **Monotonicity**
  - A monotonic curve is one in which the dependent variable always increases or decreases as the independent variable increases
- **Hysteresis**
  - The difference between two output values that correspond to the same input depending on the trajectory followed by the sensor (i.e., magnetization in ferromagnetic materials)

Dynamic Characteristics

- The sensor response to a variable input is different from that exhibited when the input signals are constant (the latter is described by the static characteristics)
- The reason for dynamic characteristics is the presence of energy-storing elements
  - Inertial: masses, inductances
  - Capacitances: electrical, thermal
- Dynamic characteristics are determined by analyzing the response of the sensor to a family of variable input waveforms:
  - Impulse, step, ramp, sinusoidal, white noise…



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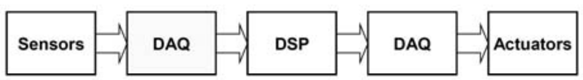
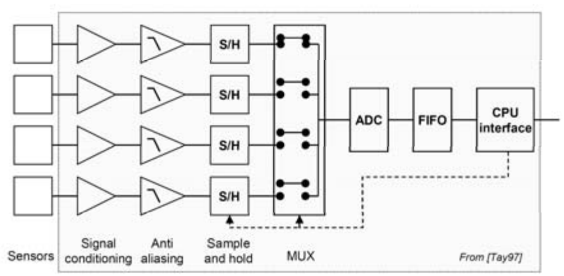
Instrumentation

Architecture of a data acquisition system





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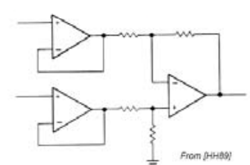
Instrumentation Amplifier

- The term INSTRUMENTATION AMPLIFIER is used to denote a difference amplifier with
  - High gain
  - Single-ended output
  - High input impedance
  - High CMRR
- High input impedance may be achieved by buffering the differential inputs.
- This solution, however, requires high CMRR both in the followers and in the final op-amp
  - Otherwise, since the input buffers have unity gain, all the CM rejection must come in the output op-amp, requiring precise resistor matching



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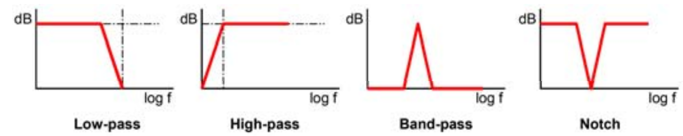
Filters

- **Filters are used to remove *unwanted bandwidths from a signal***
- **Filter classification according to implementation**
  - Active filters include RC networks and op-amps
    - Suitable for low frequency, small signal
    - Active filters are preferred since they avoid the bulk and non-linearity of inductors and can have gains greater than 0dB
    - However, active filters require a power supply
  - Passive filters consist of RLC networks
    - Simple, more suitable for frequencies above audio range, where active filters are limited by the op-map bandwidth

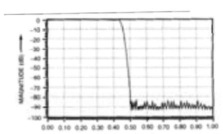
Filters

- **Filter classification according to frequency response**
  - Low-pass filter
  - High-pass filter
  - Band-pass filter
  - Band-stop (Notch)



Anti-aliasing Filters

- **An anti-aliasing filter is a low-pass filter designed to filter out frequencies higher than the sampling frequency**
  - An anti-aliasing filter should have
    - Steep cut-off and
    - Flat response in the frequency band



From [Whi96]

- **Typical filters are:**
  - Butterworth: flattest response in the frequency band but phase shifts well below the break frequency
  - Bessel: phase shift proportional to frequency, so the signal is not distorted by the filter
    - Recommended for anti-aliasing if it is important to preserve the waveform
  - Chebyshev: steepest cut-off but it has ripples in the band-pass

Intelligent and Cognitive Sensors

Capabilities of an Intelligent/Cognitive Sensor Systems

- Compensation
  - Self-diagnostics, self-calibration, adaptation
- Computation
  - Signal conditioning, data reduction, detection of trigger events
- Communications
  - Network protocol standardization
- Integration
  - Coupling of sensing and computation at the chip level
  - Micro electro-mechanical systems (MEMS)
- Others
  - Multi-modal, multi-dimensional, multi-layer
  - Active, autonomous sensing

Compensation

- Self-diagnostics versus self-calibration
  - An intelligent sensor should be able to answer the following
    - Is the output a reasonable value?
    - Does it agree with the result of an adjacent sensor?
    - Is the rate of change of the output reasonable?
    - Is the output actually changing?
- Compensation
  - Offset compensation
    - To fully utilize the dynamic range of ADCs
  - Gain
    - By means of programmable gain amplifiers
  - Linearity
    - By means of look-up tables
  - Cross-sensitivity
    - Temperature control and/or compensation

Computation

- Various degrees of computation
  - Signal conditioning (e.g., filtering)
  - Signal conversion (e.g., analog to digital)
  - Logic functions (e.g., triggering events)
  - Data reduction (e.g., feature extraction)
  - Decision making (e.g., classification)
- Advanced sensing systems have a hierarchical structure with different abstraction layers
  - LOWER LAYER performs Signal processing
    - Conditioning, filtering, conversion, contrast enhancement
  - MIDDLE LAYER performs Information processing
    - Feature generation, sensor signal fusion and parameter tuning
  - UPPER LAYER performs Knowledge processing
    - Clustering, prediction, classification, decision making, communications

Processing Techniques

- Classical
  - Statistical signal processing
  - Statistical pattern analysis
- Connectionist
  - Multilayer feed-forward neural networks
  - Unsupervised learning
- Fuzzy logic
  - Fuzzy control
  - Fuzzy signal processing
- Evolutionary
  - Genetic algorithms
  - Genetic programming
- Hybrid approaches
  - Neuro-fuzzy
  - Neuro-genetic

Communications

- Traditionally, each sensor system is custom-designed for specific applications by experience designers
- This approach has several limitations
  - Complexity: a limited number of sensors may be installed in each system, imposed by the level of complexity that human designers can deal with
  - Cost: system is composed of a small number of highly specialized, relatively expensive sensors
  - Flexibility: the resulting system cannot be easily expanded, modified, maintained or repaired. Highly trained personnel is required for these functions
- Solution
  - Standardization of transducer interfaces
    - Electrical, mechanical(?), communications protocol
  - Addition of communication capabilities
    - The ideal: Plug-and-play sensors
    - Autonomous, distributed, re-configurable sensors

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Integration

- DATA ACQUISITION
  - Instrumentation amplifiers
  - Filters
  - Sample and Hold
  - Analog to Digital Converters
  - Voltage to Frequency Converters
  - Multiplexers
  - Oscillators
  - Voltage references
  - Sensor-specific devices
  - Complete DAQ sub-systems
- COMMUNICATIONS
  - Line drivers
  - Line receivers
  - Bus transceivers
  - Bus controllers
- COMPUTING
  - Embedded
    - Micro-controllers
    - Digital Signal Processors
    - 4,8,16,32-bits
  - Monitoring devices
  - Volatile memories
    - Static RAM
    - Dynamic RAM
  - Non-volatile memories
    - ROM
    - EEPROM
    - Flash
    - Disk-on-a-chip
- CONTROL
  - Digital to Analog Converters
  - Frequency to Voltage Converters
  - Switches
  - Power drivers

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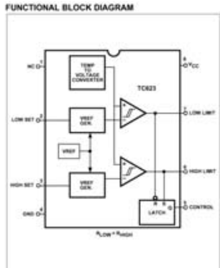
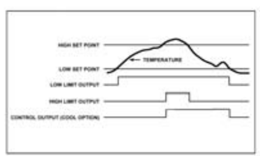
Integration

- Microchip® dual-trip temperature sensor (TC623)
  - Integrated temperature sensor and logic threshold
  - 8-pin DIP or SOIC for direct PCB mounting
  - 2 user-programmable temperature set-points (w/ external resistor)
  - 2 independent temperature limit outputs
- Application
  - Low temp reduces CPU CLK
  - High temp further reduces CPU CLK
  - Control output starts fan

FUNCTIONAL BLOCK DIAGRAM





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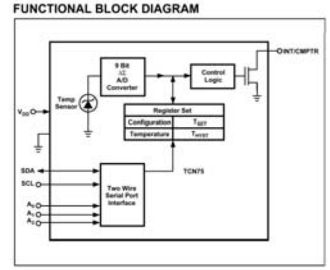
Integration

- Microchip® 2-wire serial temperature sensor
  - Standard 2-wire serial interface
    - Programmable trip point and hysteresis
    - Digital readout
    - Device configuration
  - Multiple operation modes
    - Comparator
    - Interrupt
    - Standby (power management)
- Address lines
  - Up to 8 devices can share the 2-wire bus lines

FUNCTIONAL BLOCK DIAGRAM



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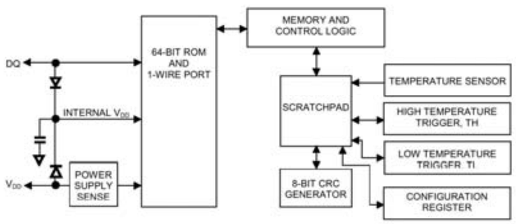
Integration

- **Dallas Semiconductor 1-Wire® digital thermometer (DS18B20)**
  - One wire interface requires only one communication pin
  - Can be powered from a data line
  - Programmable thermometer resolution from 9 to 12 bits
  - 2 and 3 wire versions are also available

DS18B20 BLOCK DIAGRAM Figure 1



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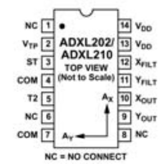
Integration

- **Analog Devices 2-axis accelerometer (ADXL202)**
  - Can measure both dynamic acceleration (e.g., vibration) and static acceleration (e.g., gravity)
  - The outputs are Duty Cycle Modulated (DCM) signals
    - Duty cycles (ratio of pulse width to period) proportional to the acceleration in each of the 2 sensitive axe
    - These outputs may be measured directly with a microprocessor counter, requiring no A/D converter or glue logic.
  - If an analog output is desired, an analog output proportional to acceleration is available from the XFILT and YFILT pins
    - or may be reconstructed by filtering the duty cycle outputs
  - Bandwidth may be set from 0.01 Hz to 6 kHz via capacitors CX and CY



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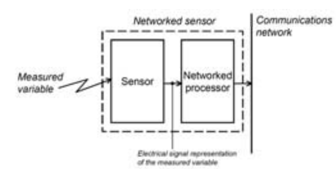
ISS Communication

Networked Sensors

- **When?**
  - Used in applications where a number of sensors are needed or where the sensor devices are distributed geographically
- **Why?**
  - Simplification of the wiring required for signal transmission
    - Assuming N nodes, full connectivity would require 2N-1-1 wires
  - Digital nature of networked signals
    - Digital transmission is relatively immune to the effects of distortion and signal degradation associated with carrying an analog signal over long distances
    - This implies that networked sensors have ADC capabilities



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Networked Sensors (cont)

- Why? (Cont)
  - Ability to communicate a much wider range of information in both directions
    - Networked sensors typically contain a local microprocessor that handles sensor signals and their transmission
  - No need to limit the microprocessor to transmission functions only
    - µP may be able to perform calibration or signal corrections
    - Sensors can be designed to have multiple sensing functions. Each signal can be handled and transmitted separately by the µP without extra connections
    - Sensors may be designed to store ID information (manufacturer, calibration parameters…)
    - Sensors may be designed to have intelligent functions, such as self-diagnostics or triggering of events
- Potential problems
  - More complex circuitry is required than for non-networked sensors
  - Quantization errors as a result of ADC
  - Network bandwidth, which may cause queuing delays or even lost data

Network Technologies

- A number of protocols exist, each one having its own interface requirements:
  - Header formats, data word length and type, bit rate, cyclic redundancy check, etc

Automotive	Sponsor
J-1850	SAE
J-1939 (CAN)	SAE
J1567 C^{2}D	SAE (Chrysler)
J2058 CSC SAE	Chrysler
J2106 Token Slot	SAE (General Motors)
CAN	Robert Bosch GmbH
VAN	ISO
A-Bus	Volkswagen AG
D^{2}B	Philips
MI-Bus	Motorola
Industrial	**Sponsor**
Hart	Rosemount
DeviceNet	Allen-Bradley
Smart Distributed Systems	Honeywell
SP50 Fieldbus	ISP+World FIP=Fieldbus Foundation
SP50	IEC/ISA
LonTalk/LonWorks	Echelon Corp
Profibus	DIN (Germany)
ASI Bus	ASI Association
InterBus-S	InterBus-S Club
Seriplex	Automated Process Control (API Inc)
SERCOS	VDW (German tool manuf. assoc)
IPCA	Pitney Bowes Inc

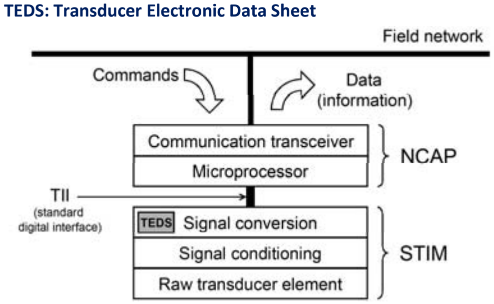
Building/office automation	Sponsor
BACnet	Building Automation Industry
LonTalk/LonWorks	Echelon Corp
IBIbus	Intelligent Building Institute
Batibus	Merlin Gerin (France)
EIbus	Germany
Home automation	**Sponsor**
Smart House	Smart House LP
CEBus	EIA
LonTalk/LonWorks	Echelon Corp
University protocol	**Sponsor**
Michigan Parallel Standard	University of Michigan
Integrated Smart-Sensor Bus	Delft University of Technology
Time-Triggered Protocol	University of Wien, Austria

Network Technologies (cont)

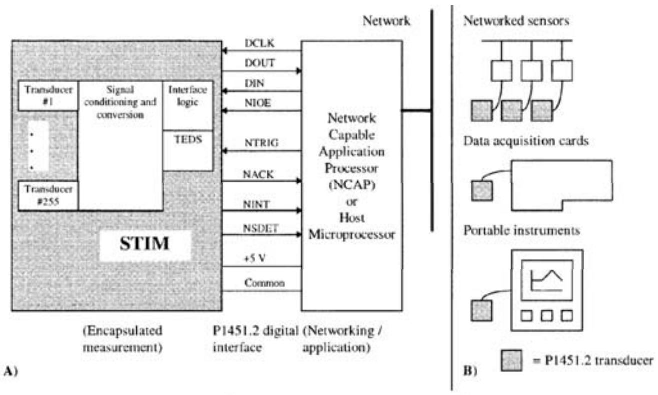
- The lack of a universal interface standard impedes the incorporation of "intelligent" features into the sensors such as
  - On-board electronic data sheets, on-board ADC, signal conditioning, device-type identification and communications handshaking circuitry
- In 1994, the IEEE and NIST decided against adopting any of the existing network protocols as a single standard (IEEE 1451)
  - A new hardware-independent standard is being developed to lower the networking entry barrier for S&A small companies
- The standard encompasses the formation of two separate software models
  - IEEE 1451.1: developing a network-independent common object model for smart transducers
  - IEEE 1451.2: enabling connection of transducers to network processors

The P1451.2 standard

- The basic building blocks
  - NCAP: Network Capable Application Processor
  - STIM: Smart Transducer Interface Module
  - TII: Standard digital interface
  - TEDS: Transducer Electronic Data Sheet



The P1451.2 standard



Features of STIM

- Single general purpose TEDS
  - A unique data structure that can support a wide variety of transducers
- Representation of physical units
  - A binary sequence encodes physical units as a product of the seven SI basic units and the 2 SI supplementary units, raised to a rational power
- General calibration model
  - Transducer calibration may be specified (linear, multi-variable, piecewise polynomial with variable segment widths and offsets)
- Triggering of sensors and actuators
  - HW trigger lines allow the NCAP to initiate sensor measurements and actuator actions, and the STIM to report completion of the requested operations
- Variable transfer rate between host and STIM
  - A field in the TEDS specifies the maximum data transport rate that the STIM can support
    - This provides flexibility for matching STIMs and NCAPs
    - Alternatively, the STIM may use a hardware line (NACK) to pace the transfer of bytes

Features of TEDS

- TEDS contains fields that fully describe the type, operation and attributes of a transducer
- TEDS is attached to and moves with the transducer
  - This way, the information necessary for using the transducer is always present
- TEDS contents
  - Mandatory
    - Meta TEDS
    - Channel TEDS
- Optional
  - Calibration TEDS
  - Application specific TEDS
  - Extension TEDS

Features of TEDS

- Meta TEDS (required, one per STIM)
  - Contains the overall description of the TEDS data structure, worst case STIM timing parameter and channel grouping information
- Channel TEDS (required, one per STIM channel)
  - Contains upper/lower range limits, physical units, warm up time, presence of self-test, uncertainty, data model, calibration model, and triggering parameters
- Calibration TEDS (optional, one per STIM channel)
  - Contains the last calibration date, calibration interval and all the calibration parameters supporting the multi-segment model
- Application specific TEDS (optional, multiple per STIM)
  - For application specific use
- Extension TEDS (optional, multiple per STIM)
  - Used to implement future and industry extensions to P1451.2

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