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# Industry 4.0: Cyber-Physical Systems and Next-Generation Sensors


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# What are Cyber-Physical Systems?

- *"Cyber-Physical Systems or 'smart' systems are co-engineered <u>interacting networks of physical and computational components</u>. These systems will provide the foundation of our critical infrastructure, form the basis of emerging and future <u>smart services</u>, and improve our <u>quality of life</u> in many areas."*

  -- NIST, Engineering Laboratory

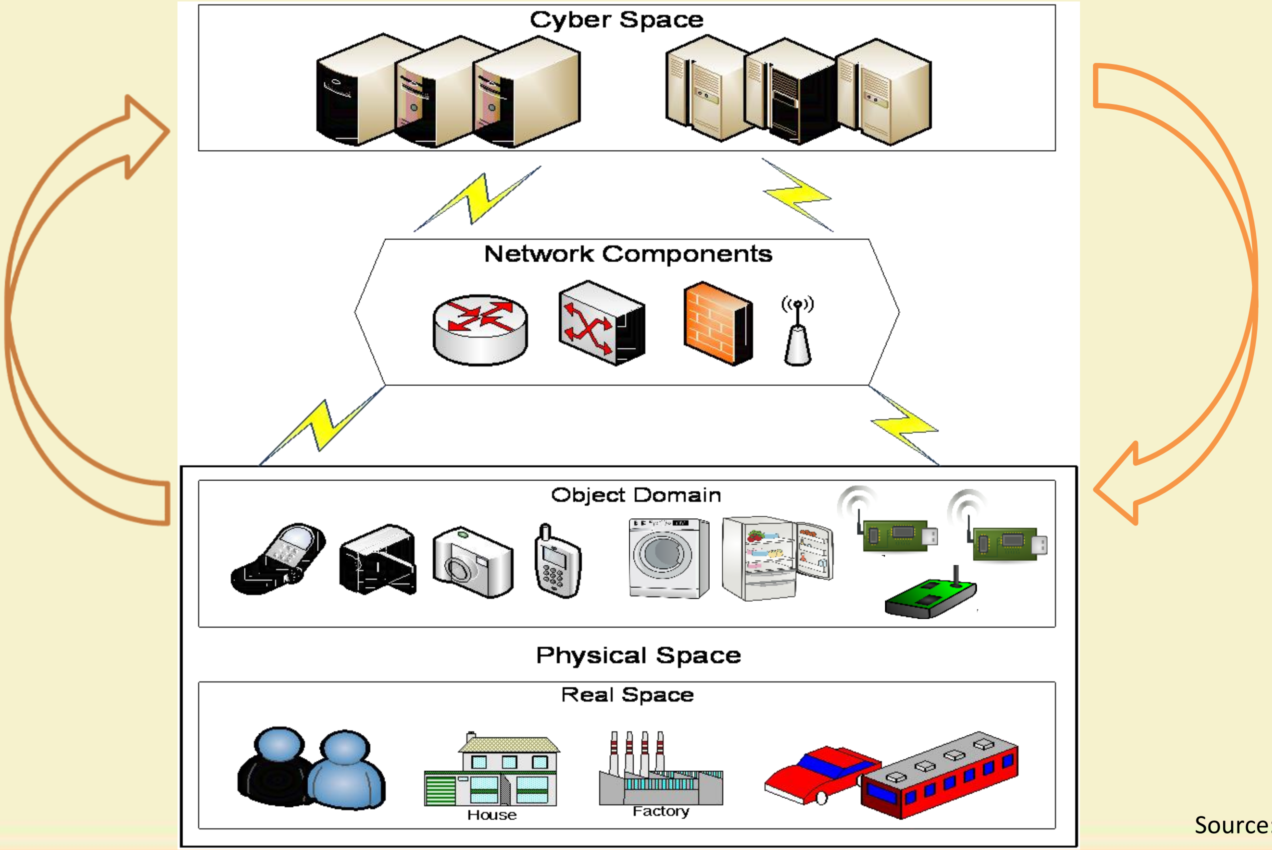
# What are Cyber-Physical Systems? (Contd.)

- Generalization of “embedded” systems
  - Possess *compute, communicate* and *control* capabilities
  - Interaction with the physical world through sensors and actuators.

- Examples:
  - Medical instruments
  - Transportation vehicles
  - Defense systems
  - Robotic equipment
  - Process monitoring and factory automation systems

Source: Lee, IEEE ISORC, 2008

Sensing




Actuation

Source: Ali et al., Sen. J., 2015

# Differences with Embedded Systems

| Embedded Systems | CPS |
|---|---|
| Devices having information processing systems embedded into them | Complete system having physical components and software |
| Typically confined to a single device | Networked set of embedded systems |
| Limited resources for performing limited number of tasks | Not resource constrained |
| Main issues are real-time response and reliability | Main issues are timing and concurrency |

Source: Lee, IEEE ISORC, 2008

# Features of Cyber-Physical Systems

- Reactive Computation:
  - Interact with environment in an ongoing manner
  - Sequence of observed inputs and outputs
- Concurrency:
  - Multiple processes running concurrently
  - Processes exchange information to achieve desired result
  - Synchronous or asynchronous modes of operation

Source: R. Alur, Principles of Cyber-Physical Systems, The MIT Press

# Features of Cyber-Physical Systems (Contd.)

- Feedback Control of the Physical World:
  - Equipped with *control systems* with feedback loop
  - Sensors sense environment and Actuators influence it
  - *Hybrid* control systems for complex tasks
- Real-Time Computation:
  - Time sensitive operations such as coordination, resource-allocation
- Safety-Critical Applications:
  - Precise modelling and validation prior to development

Source: R. Alur, Principles of Cyber-Physical Systems, The MIT Press

# Applications of CPS: Healthcare

- Highly accurate medical devices and systems
  - Image-guided surgery and therapy
  - Control of fluid flow for medicinal purposes and biological analysis
  - Intelligent operating theatres and hospitals
- Engineered systems based on cognition and neuroscience (e.g., brain-machine interfaces, therapeutic and entertainment robotics, orthotics and exoskeletons, and prosthetics)

Source: Baheti and Gill, Cyber Physical Systems, Tech. Rep., IOCT, 2011

# Applications of CPS: Transportation

- Infrastructure-based transportation CPS
  - Real-time monitoring of traffic infrastructure (traffic signals, cameras, etc.) and traffic control
- Vehicle-Infrastructure-coordinated transportation CPS
  - Transit signal priority, queue warning (for e.g., ambulances)
- Vehicle-based transportation CPS
  - Proximity detection for safety
  - Vehicle health monitoring

Source: Baheti and Gill, Cyber Physical Systems, Tech. Rep., IOCT, 2011

# Applications of CPS: Smart Grid

- Smart meters
  - Demand management with distributed generation
  - Automated distribution with intelligent substations
  - Wide-area control of Smart grids
- Phasor measurement units (PMUs)
- Data aggregation units (DAUs)

Source: Rajkumar et al., DAC, 2010

# Applications of CPS: Industry

- Manufacturing systems and logistics integrated with communication abilities, sensors and actuators
  - Smart control
  - Optimal resource utilization
  - Smart diagnostics and maintenance
- Flexibility of development of systems
- End products customized specific to needs of customers

Source: Rajkumar et al., DAC, 2010

# CPS Architecture for Industry 4.0

- Designing CPS-based manufacturing systems for Industry 4.0
- "5C architecture" comprising of 5-levels
  - Connection
  - Conversion
  - Cyber
  - Cognition
  - Configuration

Source: Lee et al., Manufacturing Letters, 2015

# CPS Architecture for IIoT: Connection

- Smart connections to ensure accurate data is obtained from the IIoT devices
- Two factors to be considered:
  - Obtaining seamless and tether-free data
  - Selection of sensors with proper specifications

Source: Lee et al., Manufacturing Letters, 2015

# CPS Architecture for IIoT: Conversion

- Conversion of machine data to meaningful information
- Data analysis tools and methodologies to be developed for
  - Prognostics and health monitoring of machine components
  - Multi-dimensional data-correlation
- Machines become self-aware

Source: Lee et al., Manufacturing Letters, 2015

# CPS Architecture for IIoT: Cyber

- Central information hub
  - Gathers system information from fleet of machines
    - Obtaining precise status information of individual machines
    - Rating of performance of individual machines among fleet
    - Predicting future behavior of machines based on historical data
  - Utilize clustering for data mining
- Machines achieve self-comparison ability

Source: Lee et al., Manufacturing Letters, 2015

# CPS Architecture for IIoT: Cognition

- Proper presentation of information to users for generating thorough knowledge of the system
- Collaborative diagnostics
- Decision making for:
  - Prioritization
  - Optimization processes

Source: Lee et al., Manufacturing Letters, 2015

# CPS Architecture for IIoT: Configuration

- Supervisory control to determine actions to be taken by the machines:
  - Self-configuration for resilience
  - Self-adjustment for variations
  - Self-optimization for disturbances
- Machines become self-adaptive

Source: Lee et al., Manufacturing Letters, 2015

# Challenges for CPS Development

- Safety, security and robustness
- Hybrid control systems
- Computational and real-time embedded system abstractions
- Sensor and mobile networks
- Architecture and modelling
- Verification, validation and certification
- Education and training

Source: Sha et al., IEEE SUTC, 2008

# Next-Generation Sensors

# Need for Next-Generation Sensors

- Interoperability of networks, transducers and control systems of different manufacturers
- Compatibility of sensors with multiple sensor actuator bus standards, reducing wiring cost and complexity
- Interconnection of analog transducers with digital networks
- Increasing usage of existing networks instead of proposing new standards

Source: Gervais-Ducouret, IEEE SAS, 2011

# What are Next-Generation Sensors?

- "Smart Sensors" –
  - Integration of sensors and actuators with a processor and a communication module.
  - Defined in IEEE 1451 Standard as:

    "Sensors with small memory and standardized physical connection to enable the communication with processor and data network"
  - Functionalities - Self calibration, Communication, Computation, Multi-sensing, Cost improvement

Source: Spencer Jr et al., J. STC, 2004

# What are Next-Generation Sensors? (Contd.)

- Limitations of Smart Sensors –
  - Pre-defined embedded functions, customization not possible
  - Narrow application spectrum
  - Sensor data aggregation not possible
  - External processor for sensor calibration
  - Basic communication protocols
- To overcome these, next generation sensors–

  "Intelligent Sensors"

Source: Gervais-Ducouret, IEEE SAS, 2011

# What are Next-Generation Sensors? (Contd.)

- "Intelligent Sensors" –
  - Capable of processing sensed data and performing pre-defined functions by processing data
  - Capable of customizing embedded algorithms on the fly
  - Capable of managing and controlling external sensors/devices
  - Comprises of a sensor, a microcontroller, a memory unit comprising of flash, RAM and ROM, and a platform for running sensor applications

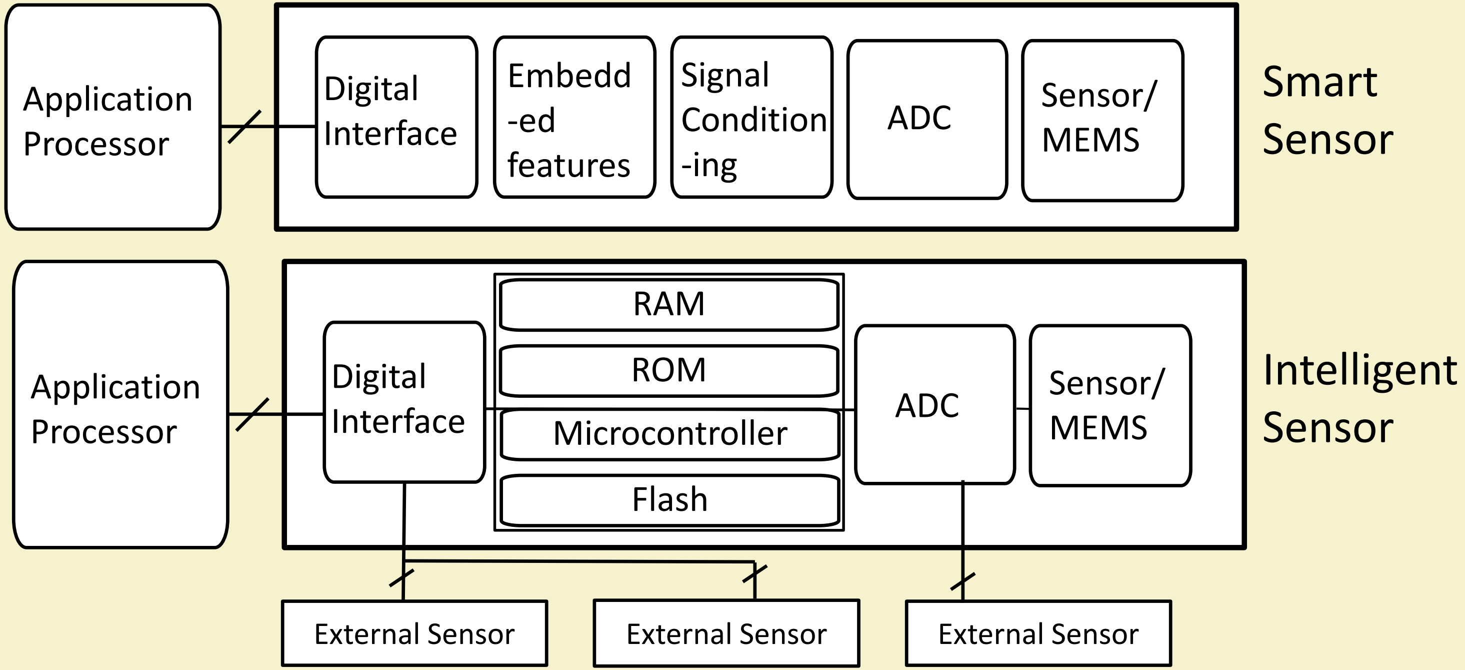
Source: Gervais-Ducouret, IEEE SAS, 2011

# What are Next-Generation Sensors? (Contd.)

- Advantages of Intelligent Sensors –
  - Reduce data communication
  - Reduced power consumption
  - Application-specific customization of sensor nodes
  - Continuous calibrating and monitoring of the sensors
  - Adaptive sampling rate and sleep-wake cycles
  - Shorter software development time
  - Improved compatibility of sensors

Source: Gervais-Ducouret, IEEE SAS, 2011

# What are Next-Generation Sensors? (Contd.)




Source: Gervais-Ducouret, IEEE SAS, 2011

# Next-Generation Sensors: Applications

- Automatic assembly in factories
- Smart fabric and intelligent textiles
- Advanced driving assistance systems
- Fault detection and forecast using machine intelligence
- Non-invasive biomedical analysis
- Chemical composition analysis
- Resource lifecycle management

Source: Gervais-Ducouret, IEEE SAS, 2011

# Next Generation Sensors: Design Challenges

- Hardware Issues –
  - Limited power
  - High response time
  - Synchronization
  - Limited bandwidth
  - Security issues
- Software Issues –
  - Software partitioning with applications processor

Source: Gervais-Ducouret, IEEE SAS, 2011

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# Thank You!!