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US NB Contributions (2 of 2) to ISO/IEC 29182 – Sensor Network Reference Architecture

Contributions toward all parts 1 – 7

Overview of Sensor Networks

Outline

- Terminology and Definitions
- On Sensor Networks – General Description
- Scope on Sensor Network Standardization
- Characteristics & Challenges: Sensor Network Requirements
- Sensor Network's Required Functions
- Sensor Network Deployment Considerations
- Sensor Network Database
- Quality of Service (QoS)
- Other Considerations for Sensor Networks
- Sensor Network Market Segments and Applications

Terminology and Definitions

Terminology and Definitions from ISO/IEC JTC 1 Study Group on Sensor Networks (SGSN)

- **Sensor**
  - A sensor is a device that observes phenomenon/phenomena, measures physical property and quantity of the observation, and converts the measurement into a signal.
- **Actuator**
  - An actuator is a device that performs a physical response caused by an input signal.
- **Sensor Node**
  - A sensor node is a device that consists of at least one sensor and zero or more actuators, and processing and networking capabilities using wired or wireless means.
- **Sensor Network Gateway**
  - The sensor network gateway represents the bridge between the sensor network itself and the backend system. Therefore, it has to provide wired/wireless interface(s) to other sensor nodes as well as a wired (e.g., Ethernet) or wireless (e.g., mobile Ethernet via WLAN, UMTS or SatCom) interface to existing IT infrastructures.

Reference [17]

Definitions (continued)

- **Sensor Networks**
  - A sensor network is a system of distributed sensor nodes interacting with each other and, depending on applications, interacting with other infrastructure in order to acquire, process, transfer, and provide information extracted from the physical world.
- **Sensor Network Services**
  - The sensor network service is the function offered by the sensor nodes or sensor networks.
- **User Services**
  - The user service is a service offered to a user by a provider. A sensor network application performs value-adding functions to sensor data according to user requirements and processing results are provided as a service to the user.
- **Sensor Network Applications**
  - The sensor network application is a use case of sensor networks supporting a set of sensor network services to users, such as, home utility monitoring and control, industrial automation, infrastructure and environment monitoring, weather and disaster condition monitoring and emergency alert. It implies software and hardware utilization that can be performed in a fully or partially automatic way and can be accessed locally or remotely.

Reference [17]

On Sensor Networks – General Description

Sensor Networks – Technologies Involved

Sensor Networks

Computational Power

General Purpose Computing
- Management of multiple tasks
  - A true platform is needed
  - Multiple application providers
- Management of local networks
- Interoperability
- Upgradeability

Embedded Computing
- Autonomy
- Self-Organization
- Reliability
- Real-time
- Management of constrained resources
  - Processing
  - Storage
  - Memory.

Network Technology

Networking
- Scalability
- Authentication and Security
- Management of wireless connectivity
  - Variable energy
  - Quality of Service
  - Diverse radio system
  - Multiple layer network hierarchy

Sensor Technology

Sensing Devices
- Acoustics
- Seismic
- Motion
- Camera/Video
- Others

Sensor Processing
- Signal processing and algorithmic development is necessary for diverse application

Power
- Intelligent power management
  - Batteries
  - Fuel cells

Reference [1], [2]

Sensor Node Components

- **CPU – Low-power processor**
  - Limited processing
- **Memory – Storage & Database**
  - Limited storage
- **Radio - Communication**
  - Low-power
  - Low data rate
  - Limited range
- **Sensors - Sensing**
  - Scalar sensors: temperature, light, etc.
  - Cameras, microphones
- **Power Supply**
  - AC (wired)
  - Batteries (wired & wireless)
- **Actuator**

Reference [15]

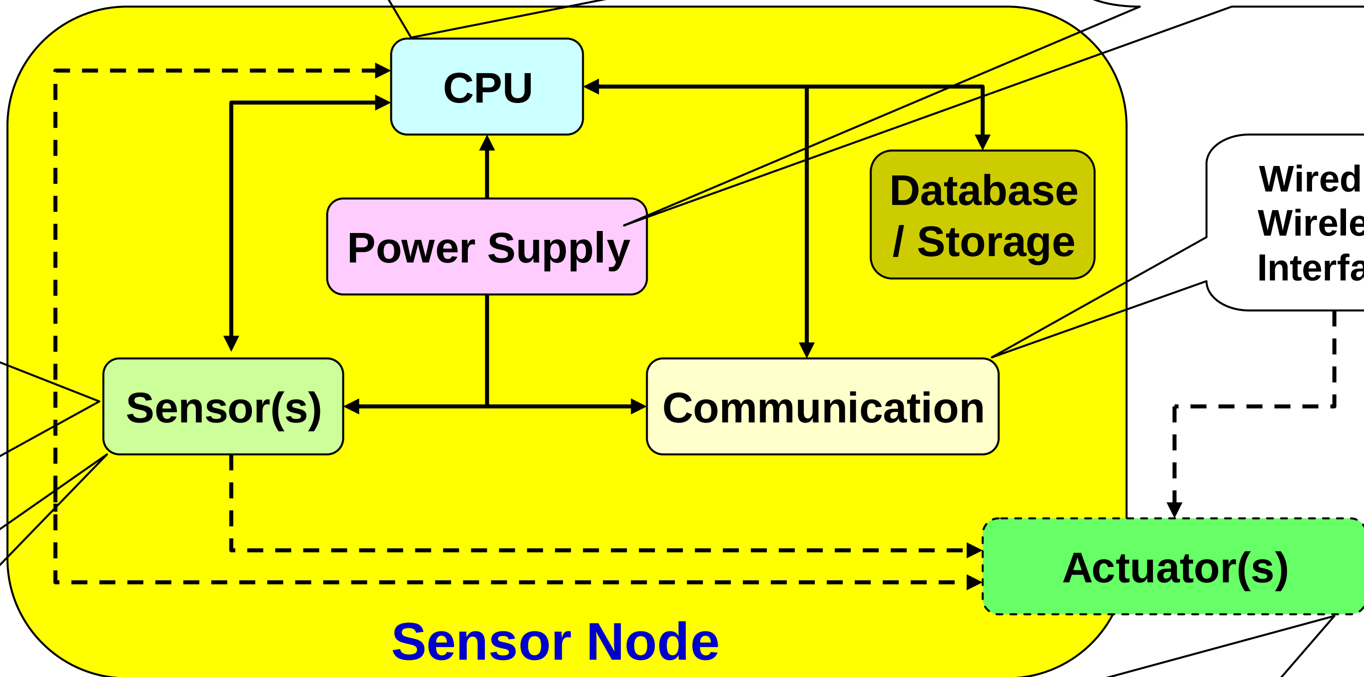
Sensor Node Internals

CPU can be embedded in the sensor, making it an intelligent sensor. It hosts OS, application algorithms and SW.

Power supply is typically batteries.

Sensing Phenomenology

Acoustic, Seismic (vibration), Magnetic, Infrared (heat), Light, Electromagnetic, Temperature, Gas, Pressure, Motion, Contaminant, objects, etc.



Wired or Wireless Interface

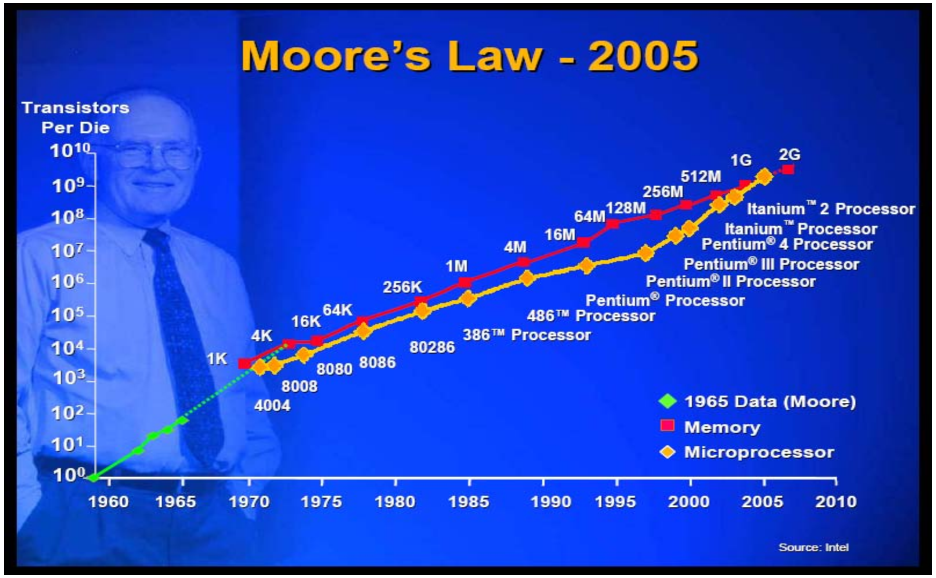
Measurement Data Output Format

1D, 2D, and 3D vs. Time

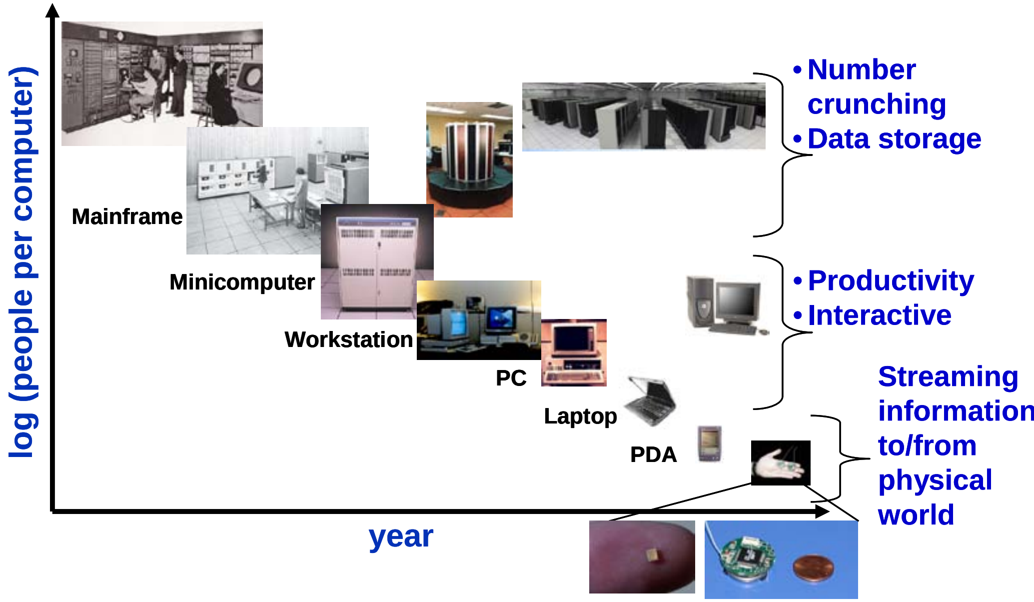
- Actuator(s) can physically embedded in the Sensor Node, or it can be remotely located away from the sensor node.
- Actuator(s) can receive information that is directly from Sensor, CPU after processing, or through wired or wireless data link (from sensor or CPU).
- Actuator(s) influence environments measured by the sensor(s).

Sensing Devices – Faster, Smaller, and Numerous

- **Moore's Law**
  - "Stuff" (transistor, etc.) doubling every 1-2 years



- **Bell's Law**
  - New computing class every 10 years



- **Cheap** – Relative: target < $1?
- **Small** – More survivable, ubiquitous, etc.
- **Many** – Economies of scale, finer measurement granularity
- **Robust** – Common case: no maintenance
- **Low-power** – No battery replacement, long-term applications

Reference [3], [4]

Sensor Networks

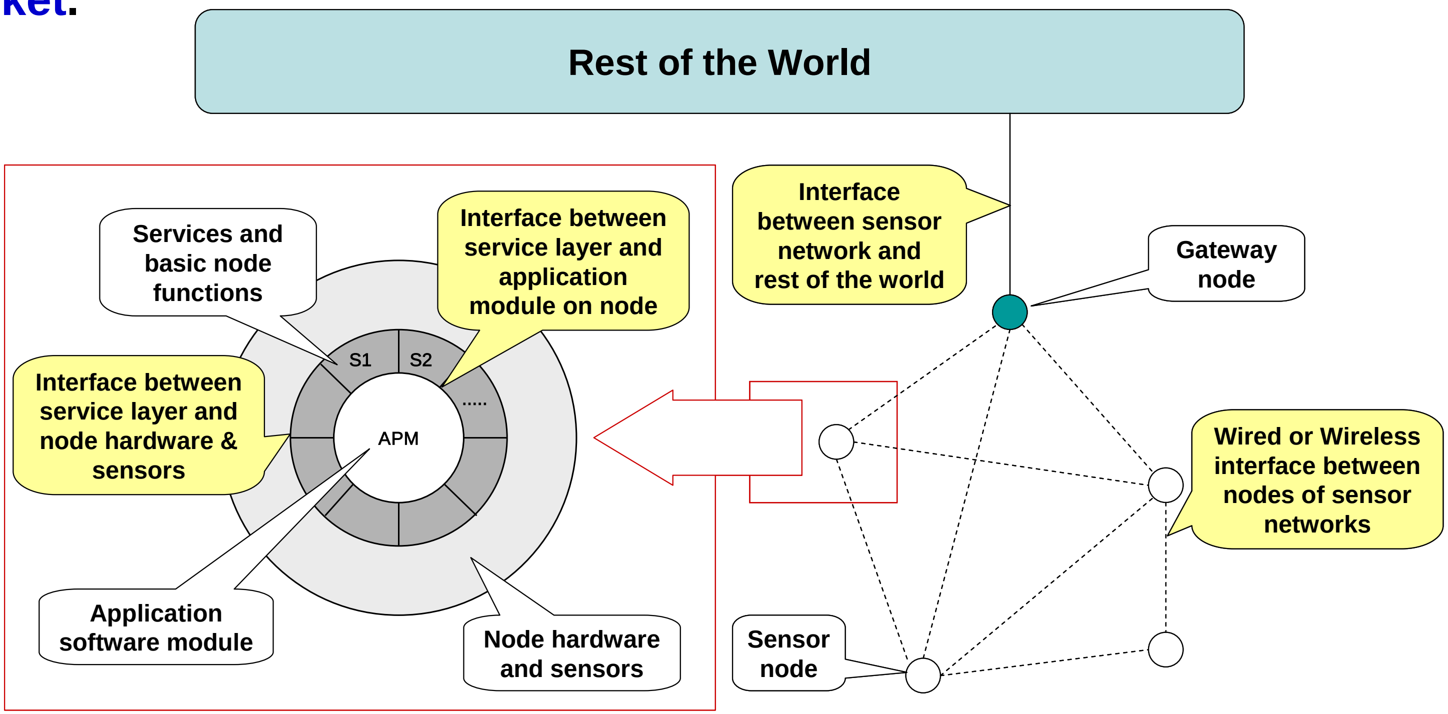
- **Our environment contains many physical processes that should be observed and/or controlled**
  - Climate control in intelligent buildings, factory floor automation, environmental control
  - Many individual sensors and actuators required
- **10s to 1000s and more of autonomous nodes that operate without human interaction.**
- **Low-power, inexpensive embedded processors (e.g., in sensor nodes) cannot perform very complex tasks**
  - But a network of such systems can be very powerful, e.g., smart sensor nodes.
  - Data from multiple sensors is processed and combined into a “big picture.”
- **Sensor coverage – Sensors can be deployed to cover a large area**
- **Reliability**
  - Redundant sensor readings
  - Resiliency to failure of individual sensors – graceful death
- **System Cost**
  - Many inexpensive sensors can be cheaper than one powerful sensor.

Reference [6, 7, 10]

Scope on Sensor Network Standardization

Scope on Sensor Network Standardization

- **Sensor networks (SN) is one of the unique technological enablers that supports both vertical (e.g., specific applications & services) and horizontal (e.g., networking) markets.**
  - SN's dual market applicability complicates the scope of SN standardization
    - **The SN standards should be sufficiently generic to be scaleable, sensor-agnostic, and protocol-agnostic to support SN infrastructure for horizontal market.**
    - **At the same time, the SN standards should encompass the common features in various application profiles (services, processing functions, interfaces, operational attributes, etc.) to support SN applications and services for vertical market.**



Reference [17]

SN Standardization Domains

- **Terminology**
- **Requirement Analysis**
- **Reference Architecture**
- **Application Profile**
- **Interface**
  - Sensor interface
  - Data types and data interface
- **Communication and Networking**
  - PHY
  - MAC
  - Networking
  - Inter-working with access and backbone networks
- **Network Management**
- **Mobility Support**
- **Collaborative Information Processing**

Reference [17]

SN Standardization Domains (continued)

- **Information Service Supporting**
  - Information description
  - Information storage
  - Identifier
  - Directory
- **Quality of Service (QoS)**
- **Middleware Functions**
- **Security and Privacy**
  - Security of sensor networks
    - **Security technology**
    - **Security management**
    - **Security evaluation**
  - Privacy of sensor networks
- **Conformance and Interoperability Testing**
  - Conformance Testing
  - Interoperability Testing
  - Performance Testing

Reference [17]

Closed vs. Open Architecture/Standard Based System

- **The utility of a closed, single threaded system:**
  - It is generally limited to a small set of application scenarios for which it is designed.
  - It is difficult to:
    - **Upgrade/update this system in the field**
    - **Design it to intelligently adapt to changing conditions in the field**
    - **Make the most effective use of its available energy in a dynamic application**
- **Open architecture/standard-based system:**
  - It is able to provide much higher levels of flexibility through the use open and standard physical and software interfaces.
  - It supports a wider suite of software and hardware modules, and hence a wider set of applications.
  - It has better capability to meet the disparate requirements for sensor networks.

Reference [2]

Characteristics & Challenges:
Sensor Network Requirements

Characteristics & Challenges: Generic Systems Requirements (1/6)

- **Communications**
  - Transmission media – Wireless (RF, Infrared, optical, etc.) or wired
  - Bandwidth-limited communication: efficiently move large amounts of sensor data for processing
  - Scheme, e.g., multi-hop wireless communication, SATCOM
- **Operation security: Security and privacy solutions**
  - Sensitive information and hostile environments
- **Scalability**
  - Handle high density of nodes, e.g., 10^2, 10^3, …, 10^6…, for different applications
  - Node position may not be pre-determined
- **Network topology**
  - Node density and mobility, new nodes, loss of nodes resulting in changing topology
  - Autonomous operation, auto-configuration, self-organizing & self-healing
  - Manual configuration is not an option; hostile environments; remote deployments
  - Large scale coordination for sensor nodes to act in concert with one another
  - Ad-hoc sensor network protocol may be applied

Reference [2], [3], [7], [13], [14], [15], [17]

Characteristics & Challenges: Generic Systems Requirements (2/6)

- **Fault tolerant**
  - Be robust against individual node failure
  - handle loss of nodes due to lack of power, physical damage, environmental interference
- **Type of services of (W)SN**
  - No simply moving bits like another networks, rather provide answer.
  - Issues like geographic scoping are natural requirements, absent from other networks
- **Quality of Service (QoS)**
  - Traditional QoS metrics do not apply
  - Still, service of (W)SN must be "good": Right info/answers at the right time
- **A variety of deployment options**
  - Manual, airborne drop, etc.
  - Capability to simulating prior to the full-scale deployment
- **Wide range of densities**
  - Vast or small number of nodes per unit area, very application-dependent

Reference [2], [3], [7], [13], [14], [15], [17]

Characteristics & Challenges: Generic Systems Requirements (3/6)

- **Coverage**
  - Network coverage, data/info retrieval scheme
- **Heterogeneity**
  - Devices with different capabilities
  - Ability to work with different types of sensors and sensor modalities; Application heterogeneity
  - Hierarchical deployment
- **Robustness/Reliability**
  - Against node failures: graceful death
- **Programmability**
  - Re-programming of nodes in the field might be necessary, improve flexibility
- **Maintainability**
  - WSN has to adapt to changes, self-monitoring, adapt operation
  - Incorporate possible additional resources, e.g., newly deployed nodes
- **Ease of Manufacturing**
- **Package size and survivability restrictions**
- **Requirements for end-to-end integration with other systems**

Reference [2], [3], [7], [13], [14], [15], [17]

Characteristics & Challenges: Generic Systems Requirements (4/6)

- **Operation lifetime**
  - The network should fulfill its task as long as possible – definition depends on application
  - Lifetime of individual nodes relatively unimportant
  - Require joint optimization process between application and implementation
- **Energy-efficient Operation: Power/energy management**
  - Energy limitation: limited transmission, computation, sensing, actuating; data routing; Physical, MAC, link, route, application
  - Lifetime of sensor network depends on battery life time (for some cases, replenishment of power is impossible)
  - To recharging large number of sensing node is impossible.
  - Need adaptable power management strategy (e.g., multi-hop communication mode, energy conservative applications)
- **Operation in varying environment**
  - Remote, unattended, etc.
  - Adjust to operating conditions and changes in application requirements
  - Survive and maintain communication, e.g., bottom of an ocean, biologically contaminate field, battlefield

Reference [2], [3], [7], [13], [14], [15], [17]

Characteristics & Challenges: Generic Systems Requirements (5/6)

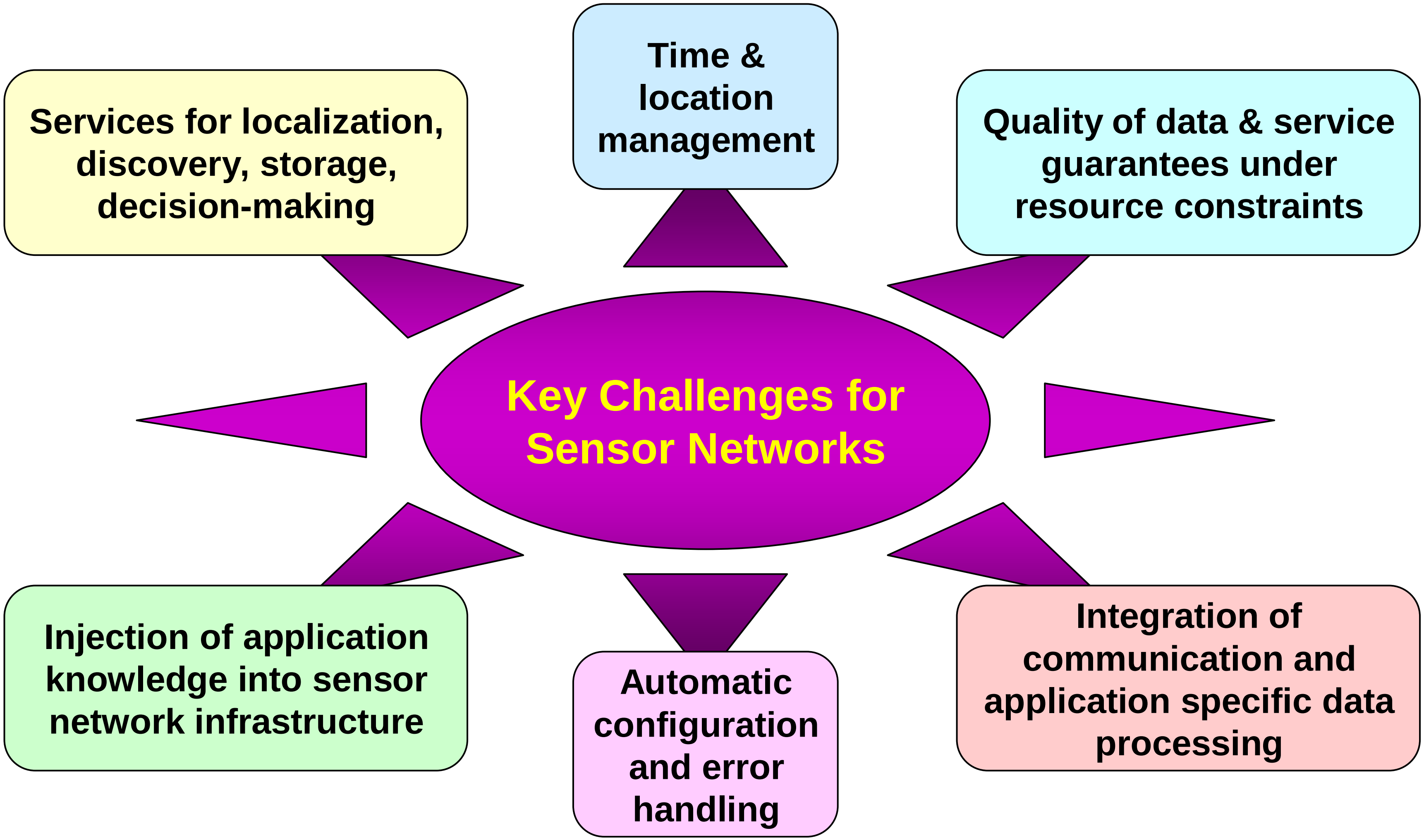
- **Task-specific application and data-centric routing**
  - Network application is defined and developed specifically for each sensing task
  - Data-centric routing is usually employed so that attribute (or location)-based naming are used.
- **Data fusion and collaborative/distributed processing**
  - Locally carry out simple computation: forward and aggregate data
  - Query for single node or group of nodes based on attribute and/or location
  - Nodes in the network collaborate towards a common goal or goals
  - Pre-processing data in network (as opposed at the edge) can greatly improve efficiency
  - Base nodes (or gateway) collect data from given area and generate summary messages
  - Need algorithms that are not centralized, i.e. do not require all of the data
  - Real-time computation for certain applications: Must be processed faster than new data is generated

Reference [2], [3], [7], [13], [14], [15], [17]

Characteristics & Challenges: Generic Systems Requirements (6/6)

- **Deeply distributed architecture**
  - Localized coordinate to reach whole system goals, no infrastructure and central control support
- **Production Costs**
  - Make them low costs – cost of single node is very important to justify the overall cost of the network
- **Hardware Constraints**
  - Low cost (throw-away) sensors, low power requirements
  - Nodes are tiny – limited processing/memory capabilities, limited battery size
- **Application configuration**
  - Absolute or relative physical location determination
  - Self-organize into functional clusters
- **Computation**
  - Signal/image/information processing algorithms
  - Network protocols

Key Challenges for Sensor Networks



Functional Requirements for SN - Services

- Long Range Communication Service
- Short Range Communication Service
- Clustering Service
- Routing Service
- Installation Service
- Security and Privacy Service
- Data Storage Service
- Collaborative Processing Service
- Control Service
- Linkage Service
- Orientation Detection Service
- Self-Localization Service
- Monitoring Service for Communication Links
- General Sensing Service
- Time Synchronization Service
- Identification Service
- Data Entry Service
- Indication Service
- Display Service
- Sensor Interface
- High Data Rate Communication Service
- Low data Rate Communication Service

Reference [17]

Sensor Network's Required Functions

Data Aggregation

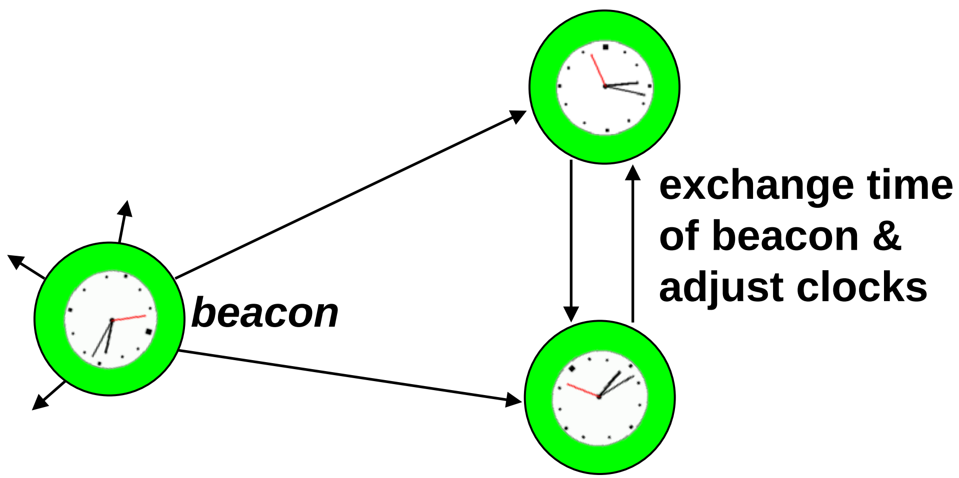
- Combines data from many sensors into a more compact form before forwarding to a location for processing
- Needed to handle the large amount of data generated in sensor networks
- Parameters: efficiency, speed, etc.

Forwarding vs. Aggregation

Reference [7]

Clock Synchronization

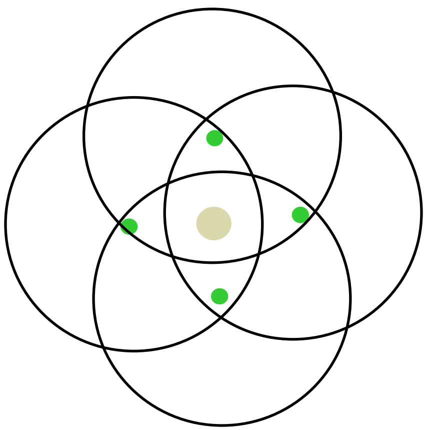
- **Sensors' clocks drift slightly over time**
- **Need to periodically adjust the local clocks so that time is consistent throughout the network**
- **Especially important for sensors around same joint or group/cluster to detect failures**
- **Parameters: precision, update frequency**



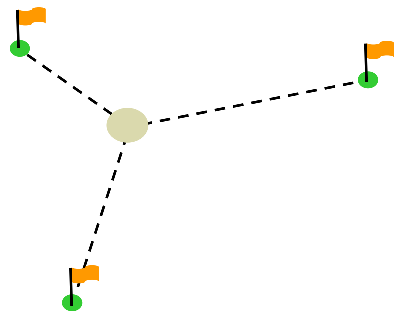
Reference [7]

Localization

- **Determining the physical locations (absolute or relative positions) of the sensors, in many application scenarios, is important.**
- **If thousands of sensors are deployed, don't want to enter their locations by hand; and explicitly providing this information is not acceptable.**
- **Use sensing or network connectivity to infer physical location**
- **The localization can be obtained from:**
  - External sources like GPS
  - RF-based solutions only
  - A combination of RF and ultrasound techniques.
- **Parameters: precision, efficiency**



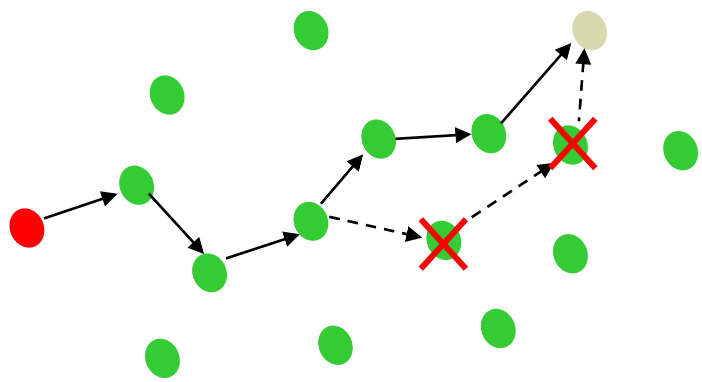
Proximity



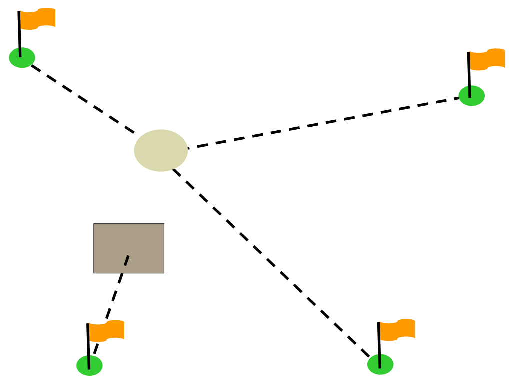
Triangulation

Fault Tolerance

- Some sensors will fail.
- Due to the large number of sensors in (W)SNs, faults can be common.
- The network needs to keep working, even if with diminished capacity.
- Parameters: resiliency, response time



Alternate Routing



Less accurate triangulation

Reference [7]

Collaborative Data/Information Processing: Distributed Computing Infrastructure (1/3)

- **Designing Distributed Sensor Architectures**
  - Server-oriented or centralized fusion approach
    - **Data migrates to server from sensors**
    - **Store or not store?**
    - **When should data migrate?**
    - **How should data migrate in its original raw form or in some aggregated form?**
  - Distributed processing or distributed fusion approach
    - **Data does not migrate, requests/queries migrate**
    - **Database (e.g., Tiny DB) approach**
- **Middleware – Common Operating Environment (COE)**
  - Well designed middleware supports effective/efficient collaborative processing for sensor networks
    - **Energy-Efficiency**
    - **Real-time**
    - **Fault tolerance**

Reference [12]

Collaboration Among Nodes (2/3)

- **Sensor nodes collaborate to extract and process measured data turning them into information. There are two types of collaboration:**
  - Intra-node collaboration
    - **Multiple sensing modalities, e.g., combining acoustic and seismic measurements**
    - **No communication burden since collaboration is at a particular node**
    - **Higher computational burden at the node**
  - Inter-node collaboration
    - **Combining measurements at different nodes**
    - **Higher communication burden since data is exchanged between nodes**
    - **Higher computational burden at a manager node, e.g., gateway**

Main Characteristics in Collaborative Processing (3/3)

- **Correlated observation**
  - Data from nearby nodes cannot be assumed independent when the nodes measure a physically realizable process.
    - **Opportunities for distributed algorithms for signal processing**
- **Cooperation among nodes**
  - Before communication with the far receiver, nodes can coordinate their use of scarce communication resources
    - **Opportunities for distributed algorithms at the physical layer**
- **Multiple access**
  - Interference arises when multiple nodes share a common medium that needs to be either mitigated or exploited somehow
    - **Opportunities for distributed algorithm at the MAC layer**

Reference [5]

Groups in Sensor Networks (1/3)

- **Why Groups?**
  - Some tasks cannot be performed by a single sensor
  - Sensors and related actuator form a natural group
  - Redundant deployment of sensors
  - To increase reliability, algorithms should not rely on single nodes
- **Definition of groups**
  - Clusters: Nodes in proximity (radio range)
  - Identity groups: Group members are explicitly enumerated
  - Semantic groups: Group members are defined implicitly based on shared information, properties, common tasks, etc.
- **Group communication is natural for sensor networks**
- **Taming the complexity of large sensor networks can be tackled by introducing hierarchies.**
- **Some types of hierarchies exploit immediate vicinity of nodes by grouping them into clusters and exploit these cluster for a number of different tasks such as routing or data aggregation.**

Reference [6], [8]

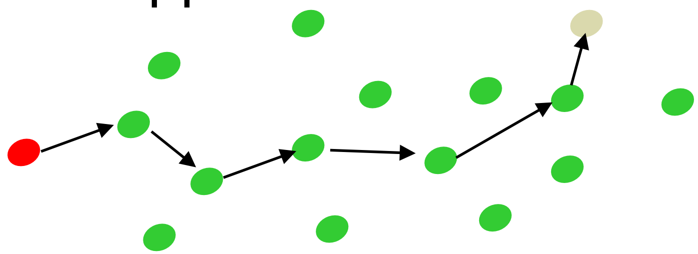
Groups in Sensor Networks (2/3)

- **Challenges in Group Management**
  - How to negotiate gap between groups and clusters?
  - Group management depends on application
  - Group communications
  - Mobility of nodes or sensed phenomenon
  - Link and node failures (mobility vs. failure)

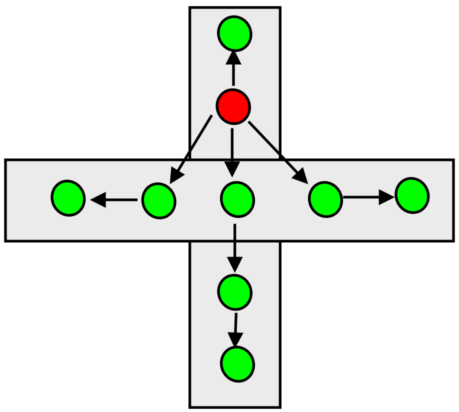
Reference [6]

Routing and Group Communication (3/3)

- **Routing delivers messages to a specific node in a network**
  - Multi-hop, ad hoc
  - Old problem, but needs new approach in the sensor network environment



- **Group communication (multi-cast) delivers messages to a subset of nodes in the network**
  - Needed to communicate to groups of sensors



- **Parameters: reliability, efficiency, power consumption**

Reliability

- **Reliability of wireless is less than wired**
- **Range dependent on environment**
- **Acceptable Probability of:**
  - Missed information
  - Erroneous information
  - Late Arrival of information
  - Unauthorized interception
- **Ultimately, no solution is 100%.**
  - No silver bullet

Reference [16]

Importance of Power

- **Wireless devices are internally powered.**
- **Battery power density is very low.**
  - Efficient power use is critical.
- **Local, parasitic power:**
  - Solar Cells
  - Wind
  - vibration, etc.

Every bit processed/transmitted is one bit closer to a dead battery.

Reference [16]

Sensor Network Deployment Considerations

Deployment Options for Sensor Networks

- **How are sensor nodes deployed in their environment?**
  - Dropped from aircraft: ***Random deployment***
    - **Usually uniform random distribution for nodes over finite area is assumed**
  - Well planned, fixed: ***Regular deployment***
    - **Not necessarily geometric structure, but that is often for convenience**
    - **Typically for well-known environments, e.g., factory floor for preventive maintenance.**
  - ***Mobile*** sensor nodes
    - **Can move to compensate for deployment shortcomings**
    - **Can be passively moved around by some external force (e.g., wind, water)**
    - **Can actively seek out "interesting" areas**

Reference [3]

Deployment Issues – Time and Space

- **Sensor node localization**
  - Absolute or relative position
  - Self-positioning vs. remote-positioning
  - Multiple techniques for locating sensors
    - **Measure proximity to landmarks**
    - **Position relative to initialization position**
    - **Measure distance of landmarks – Ranging**
- **Temporal synchronization**
  - Reference-broadcast synchronization: very high precision sync with slow radios
  - Post-facto synchronization – only when needed.
  - Peer-to-peer synchronization – No master clock
  - Tiered architecture – Range of node capabilities
- **Scale of operations: Temporal and Spatial**
  - Sampling
  - Extent
  - Density

Reference [1]

Deployment Issues – Energy Issues

- **Energy drains by**
  - Processing
  - Communications
  - Sensors
  - Actuators
  - Power supply
- **Energy management**
  - Processor energy management
  - Communication energy management
  - Others

Reference [1]

Sensor Network Database

Sensor Network Databases

- **From a data storage point of view, a sensor network database is:**
  - A *distributed* database that *collects* physical measurements about the environment, *indexes* them, and serves *queries* from users and other applications external to or from within the network.
  - Combination of sensor data (time-stamped measured data) and stored data (sensor location, types of sensor, etc.) from every sensor in the sensor network
- **Designing properties to consider:**
  - Persistence: Data stored much remain available to queries despite sensor node failures and changes in the network topology
  - Consistency: A query must be routed correctly to a node where the data are stored
  - Controlled access to data: different update operations must not undo one another's work, queries must always see a valid state of the database
  - Scalability in network size: as the number of nodes increases, the total storage capacity should increase and the communication cost should not grow unduly
  - Loading balancing: Storage should not unduly burden any node, nor should a node become a concentrated point of communication
  - Topological generality: Database architecture should work on broad range of network topologies.

Reference [10]

Challenges in Sensor Network Database

- **Dynamic data streams**
- **Hardware resource limitations**
  - Limited per-node computing power and storage
  - Unreliable wireless communication
  - Battery power supply
- **Complex, networked, embedded software**
  - Blurred boundaries between components
  - Plenty of cross optimization opportunities

Reference [11]

Quality of Service (QoS)

Quality of Service (QoS)

- **Traditional QoS**
  - Network level: Delay, throughput, etc.
    - **Known to be largely irrelevant**
  - Application level: Perceptual QoS metrics
    - **Mean opinion score for voice**
    - **Image quality metrics**
    - **Much more important and useful**
  - Not adequate for WSN

- **Types of Well-Known QoS**
  - Latency
    - **Shows utility drops as answers take longer to achieve**
  - Value-based
    - **Shows which output value are most important**
  - Loss-tolerance
    - **Shows how approximate answers affect a query**

- **What are appropriate QoS metrics for (W)SN?**
  - What is the *service* of a (W)SN?
  - What is its *quality*?

Reference [9], [12]

Service of a (W)SN

- **Provide information**
  - Measurements of some physical processes
  - Appropriately aggregated, condensed, put into perspective
  - “People want answers, not numbers” (S. Glaser)
- **Making decisions**
  - Decide how to control certain actuators
  - Actuators in networks will become increasingly important

Quality of Information/Decision

- **What is Accuracy?**
  - Measure of the discrepancy between:
    - **The real-world values and the provided results**
    - **The correct/optimal decision and the taken one**
    - **Time is implicit part of accuracy**
  - Resolution
    - **Temporal**
    - **Spatial**
  - Value laxity
    - **Value represented as an interval**
    - **Value represented as a probability distribution**
- **What is Precision?**
  - Probability with which a given accuracy is achieved
    - **Limited by error, time elapse, etc.**

Reference [9], [12]

Quality of Operation

- **Energy per Operation**
  - Energy can be the most limiting factor to accuracy/precision.
- **Lifetime**
  - Related to, but not equivalent with energy
    - **Critical nodes are the focus**
  - As operational time of the network progresses, accuracy will suffer
    - **Energy drainage**
    - **Calibration drift**

Reference [9]

Quality of Deployment

- **Cost**
  - Deployment will influence overall quality
    - **Typical example: almost a 0/1 behavior for connectivity/size of largest component as function of number of neighbors**
  - Assume a fixed budget available for a WSN solution, how to split it?
    - **More nodes? Nodes with bigger batteries? Fewer, but more complex nodes?**
    - **Consider cost in design decisions**
  - What are cost-quality-density tradeoffs?

Reference [9]

Quality Relation and Requirements

- **Quality Relations**
  - In general, a set of feasible attributes, e.g., accuracy, precision, energy/power, lifetime, and cost, has to be characterized.
  - Perhaps not in detail, but principal behavior characteristic need to be explored
  - How can we achieve lower and upper bound of acceptable qualities of services?
- **Quality Requirements**
  - Wide open field
  - Considerations
    - **How much energy should be spent for a given operation?**
    - **What is the smallest required accuracy?**
    - **Lifetime target?**
    - **Cost is deployment, planning, management issues**

Reference [9]

Other Considerations for Sensor Networks

Maintenance Options

- **Feasible and/or practical to maintain sensor nodes?**
  - Replace batteries?
  - Unattended operation?
  - Mission lifetime?

- **Power/Energy supply?**
  - Limited from point of deployment?
  - Recharging, energy scavenging from environment?
    - **Solar cells**
    - **Wind**
    - **Vibration**
    - **Others**

Reference [3]

Economic Issues

- **Material Costs**
- **Labor Costs**
  - Installation
  - Operation
  - Maintenance
- **Reliability**
- **Power/Energy**
- **Hidden Costs**

Reference [16]

Sensor Network Market Segments and Applications

Sensor Data Access Needs of Applications

- **Historical data**
  - Analysis to better understand the physical world
- **Current data**
  - Monitoring and control to optimize the processes that drive the physical world
- **Future data**
  - Forecasting trend in data for decision making.

Reference [12]

Sensor Networks Markets & Applications (1/4)

- **Logistics and Supply Chain Management**
  - Monitoring of hazardous goods and chemicals
  - Theft prevention in distribution systems for high value goods
  - Container monitoring in global supply chains
- **Energy & Utility Distribution Industry**
  - Sensor network-based smart grid system
  - Automated meter reading
- **Automation, monitoring, and control of industrial production processes**
  - Industrial automation (in general)
  - Machine condition monitoring
  - Control of manufacturing robots
- **Healthcare and Medical Assistance at Home and in Hospital**
  - Position & posture monitoring
  - Hospital personnel and equipment tracking
  - Care for elderly people

Reference [17]

Sensor Networks Markets & Applications (2/4)

- **Civil Protection and Public Safety**
  – Monitoring of building integrity for bridges, tunnels, etc.
  – Early warning systems for detection of emerging forest fires
  – Localization and monitoring of fire fighters and rescue personnel
- **Learning, Education, and Training (LET)**
  – LET collaboration application areas
  – LET multi-media based collaboration
  – LET biometric feedback application area
- **Automation and Control of Commercial Building an Smart Homes**
  – Building energy conservation system
  – Adaptation of living environment to personal requirements
  – Monitoring and control of light using sensors
- **Automation and Control of Agriculture Processes**
  – Monitoring of growing areas
  – Crop disease management
  – Nutrient management

Reference [17]

Sensor Networks Markets & Applications (3/4)

- **Intelligent Transportation and Traffic Control**
  - Parking management system
  - Harbor freight intelligent management system
  - Advanced vehicle and highway information system
- **Environment Observation; Forecasting, and Protection**
  - Detection of water pollution in nature reserves
  - Seismic sensing and flood monitoring
  - Weather observation and report
- **Facility Management**
  - Management of offices and large buildings
  - Management of industrial sites
  - Management of transport infrastructure (road, tunnels, bridges)
- **Asset Management**
  - Management of medicine and medical devices in hospital
  - Blood bag monitoring and status tracking
  - Management of tools, e.g., in aviation industry

Reference [17]

Sensor Networks Markets & Applications (4/4)

- **Defense and Military**
  - Battlefield monitoring
  - CBRN threat detection
  - Military vehicle operations and maintenance
- **Homeland Security**
  - Disaster and crisis management
  - Border control and virtual fences
- **Retail Business**
  - Automated inventory management
  - Security systems and theft prevention
- **Research**
  - Habitat monitoring
  - Remote ecological sensor networks
- **Active Tags / Mobile RFID**
  - Personnel tracking (e.g., coal mine security)
- **Ship & Airline Monitoring and Control**
  - Air traffic management and control
  - Ship tracking and container tracking
- **Space Exploration**
  - Planetary remote sensing for scientific research

Reference [17]

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