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Contrast with Traditional Systems

3.1 Problem Statement

Sensor networks are a fundamentally new type of system. Computing systems up to now have been primarily user-centric. Desktop devices interact directly with a human operator following their instructions. Networked systems served primarily as communications devices between human users. These communications were often augmented by the existence of databases for transaction processing. Information was retained and processed for later use.

Sensor networks now provide distributed systems that interact primarily with their environment. The information extracted is processed and retained in databases as before, but the human is removed from many parts of the processing loop. Devices are designed to act more autonomously than was previously the case. They are also designed to work as a team.

Embedded systems are not new, but sensor networks greatly extend the capabilities of these systems. Up to now, embedded systems were resource-constrained devices providing limited intelligence in a strictly defined workspace. Sensor network research is aiming towards developing self-configuring systems working in either unknown or inherently chaotic environments.

Network communications needs to be handled in a new manner. Data are important because of their contents and not because of the machine from where it originates. Wireless transmission is expensive, making it attractive to process data close to the source. The problems of multi-path fading, interference, and limited node lifetimes combine to make data paths, even under good conditions, transient and unreliable. The implications this has for network design should not be underestimated.

Similarly, signal-processing technologies need to be aware of transmission delays and the volume of data needed. The resources consumed by an implementation, and the latencies incurred, are an integral part of any sensing solution. In short, all levels of the networking protocols need to be considered as a single gestalt. Beyond this, system design requires new power-aware computing hardware and operating systems.

Embedded sensors are now part of large, loosely coupled networks with mobile code and data. Data supply and demand are stochastic and unpredictable. Processing occurs concurrently on multiple processors. Applications are in hostile environments, with noise-corrupted communication and...
failure-prone components. Under these conditions, efficient operation cannot rely on static plans. Van Creveld [1] has defined five characteristics that hierarchical systems need to adapt to this type of environment [2]:

- Decision thresholds fixed far down in the hierarchy.
- Self-contained units exist at a low level.
- Information circulates from the bottom up and the top down.
- Commanders actively seek data to supplement routine reports.
- Informal communications are necessary.

Organizations based on this approach have been successful in market economies, war, and law enforcement [3].

Data requests from a declarative programming language pull data by making requests. Sensors push information by providing sensor data. Requests and data follow paths of least resistance through intermediate nodes. Mobile data and code allow signal processing and automatic target recognition to be done during data transmission. Processing includes decomposition, compression, and fusion of sensor data. This is done robustly and efficiently by giving each node the ability to make limited local optimizations based on locally available information.

The sensor network consists of nodes integrating these abilities. Requests for information form flexible ad hoc virtual enterprises of nodes, allowing the network to adapt to and compensate for failures and congestion. Complex adaptive behavior for the whole network emerges from straightforward choices made by individual nodes.

The final system will be a virtual enterprise. Groups of components form flexible ad hoc confederations to deliver data in response to changing needs and resources. This is applicable to any sensing modality and can be implemented on any testbed containing networked processors, sensors, and embedded processors.

Factors needing to be considered for system optimization include

- Data format for transmission
- Paths taken through the network for requests and data
- Points where fusion should occur during transmission
- Processing to be performed by mobile code during data transit

The final issue to consider is adaptation to system state. Information can be exchanged in a number of formats. It is reasonable to compress data for transmission over slow channels. Transmission over noisy channels requires redundant data. As noise (lack of noise) is detected in a channel, error checking increases (decreases). The meta-protocol starts with pessimistic assumptions of channel quality and modifies the protocol dynamically. Modifications are based on information from normal operations. Extra traffic for monitoring status is to be avoided.

Sensor networks are fundamentally different from their predecessors. Some of these differences are a matter of degree:

- Number of nodes required
- Power constraint severity
- Proximity to hostile environment
- Timeliness requirements

In the final analysis, the most important differences are the fundamental differences in the way information technology is used. Computer networks are no longer sensitive devices being coddled in air-conditioned clean rooms. They are working in hostile conditions. Sensor networks respond to the needs of human users. How they respond, and their internal configurations, will be decided independent of human intervention.
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References
