Applications of Sensor Network Data Management

Farnoush Banaei-Kashani
Department of Computer Science
University of Southern California
Los Angeles, CA 90089
banaeika@usc.edu
http://persis.usc.edu

Cyrus Shahabi
Department of Computer Science
University of Southern California
Los Angeles, CA 90089
shahabi@usc.edu
http://infolab.usc.edu

SYNONYMS

Applications of Sensor (Network) Databases

DEFINITION

Sensor networks allow for micro-monitoring of different phenomena of interest in arbitrary physical environments. With this unique capability, sensor networks can capture the events in the real world as they happen in the form of high-resolution spatiotemporal data of various modalities, and provide the opportunity for real-time querying and analysis of the data for immediate response and control. Such functionality is desirable in many classic applications while enabling numerous other novel applications. From the data management perspective, there is a consensus among database researchers that management and analysis of the massive, dynamic, distributed and uncertain data in sensor network applications is going to be one of the new grand challenges for the database community:

> *"Sensor information processing will raise many of the most interesting database issues in a new environment, with a new set of constraints and opportunities."*
>
> Excerpt from the Lowell Database Research Self-Assessment[1]

HISTORICAL BACKGROUND

Shortly after the introduction of the sensor networks and their potential applications about a decade ago [1], management of the sensor data was recognized as one of the main challenges in realizing the sensor network applications [2].

SCIENTIFIC FUNDAMENTALS

Sensor Databases

One can think of a sensor network as a distributed database that collects, stores and indexes the sensor data to answer the queries received from external users/applications as well as internal system entities. By considering a sensor network as a database, one envisions some of the benefits of the traditional databases potentially for sensor databases; e.g., reduced application development time, convenient multi-user data access and querying with a well-defined generic

[1] By a group of thirty senior database researchers, *"The Lowell database research self-assessment"*, Communications of the ACM, Volume 48, Issue 5, May 2005.

interface, efficient data reuse, and most importantly data independence. Physical data independence is a particularly beneficial advantage of the sensor database approach, because as compared to the physical layer of the traditional databases the physical infrastructure of the sensor networks is much more sophisticated. With physical data independence in sensor databases, the logical schema of the data exposed to the users is separated from the physical schema that defines the complex and probably changing implementation of the data structures and operations on the physical network. By separating the logical and physical schemas, users/applications are isolated from the typical complications of the distributed data processing in the volatile sensor networks and can focus on designing the logical structure of their queries; hence, the use of the sensor data is significantly facilitated.

Sensor Database Distinctions

Sensor databases are different from traditional distributed databases in both physical specifications and data characteristics. At the physical level, nodes of the database (i.e., sensor nodes) are severely constrained in resources, such as memory space, storage space, CPU power, and most importantly energy. Moreover, in sensor databases nodes and links of the network are both highly volatile. On the other hand, with sensor devices continuously collecting measurements from the environment, sensor data is naturally very dynamic. Besides, due to inaccuracy of the sensor devices, signal interference, noise, etc., uncertainty is also an inherent characteristic of the sensor data. With such physical and data characteristics, maintaining the illusion of a database is arguably a more difficult objective with sensor databases as compared to that of the traditional distributed databases, and accordingly, requires new data management solutions:

- Database operators should be delay-tolerant, and tolerant to frequent updates of the data
- Query execution should be performed *in-network* for energy efficiency; similarly, data storage and access should be designed for energy efficiency
- Data acquisition plan is required to determine what data to collect
- Sensor query language should be augmented with new operators to specify duration and sampling rate of the data acquisition
- Query execution plan should be dynamically optimized to account for variable access delay and uncertain data availability
- Data uncertainty should be accounted for
- Volatility of the sensor network should be hidden to provide the illusion of a stable database
- Continuous queries should be supported, as sensor networks are primarily used for long-term monitoring
- Meaningful data digests should be maintained to allow for answering historical queries, since data is continuously collected despite the limited space for storage
- Aggregate spatiotemporal queries and range queries should be supported, for energy efficiency [3,4]
- Approximate queries should be supported, as they are more meaningful with sensor data
- Triggers should be supported for the event-driven monitoring applications

One approach to implement sensor databases is to transfer all data to one or a small number of external base stations, where a traditional database system can be exploited. Alternatively, the data can be stored within the network itself with a balanced and optimal data storage plan. Although with the first approach one can more conveniently employ and extend the data management solutions applicable with the traditional databases, the second approach, termed *in-network storage*, allows for tighter coupling between query processing, on the one hand, and networking and application semantics, on the other hand. Tight coupling can potentially enable more energy efficient query processing in sensor databases. To evaluate the query processing performance with a particular sensor database implemented with either of these approaches, one can use the standard distributed database performance metrics such as incurred communication cost, query time, indexing time, throughput, load balance among nodes, data update overhead and storage requirements.

KEY APPLICATIONS

As compared to the traditional wireline sensor networks that have been in use for decades, the more recent wireless sensor networks enable low cost and rapid deployment of the sensing network while supporting mobility. With these desirable characteristics due to the wireless technology, recently the standard applications of the sensing networks are revived and new applications that were otherwise unthinkable are identified. The key classes of applications for sensor databases/networks are discussed below.

Environmental Monitoring

Environmental monitoring applications, specifically habitat monitoring [5], are among the earliest applications of the sensor networks. With the habitat monitoring applications, sensors are deployed to monitor animals or plants in their original habitats with most convenience for the scientists and least disturbance for the wildlife. With other environmental applications, sensors can be used to collect earth-science and atmospheric data for environmental explorations, such as the study of the air pollution, global warming, etc., and also early detection and prediction of the natural and man-made disasters, such as hurricanes, wildfires, earthquakes and biological hazards.

Military Intelligence

With rapid deployment, and inexpensive and untethered sensors, wireless sensor networks are well positioned as the tool to collect battlefield data for real-time battlefield intelligence [6]. For instance, wireless sensors can be utilized for geofencing (i.e., deploying a sensor network as a transparent fence to protect an area against unauthorized trespassing), enemy tracking, and battlefield exploration and condition assessment particularly in hazardous environments. In military intelligence applications, the small form-factor, reliability, interoperability and durability of the sensor nodes under severe environmental conditions are particularly critical requirements.

Asset Management

Businesses with large and high-turnover inventories of assets (such as construction companies, utility companies and trucking companies) can extremely benefit from automated asset management systems in improving the utilization of their resources [7]. With automated asset management, sensor networks are deployed to collect real-time data about exact location and condition of an inventory of assets automatically. The collected data provides the opportunity for real-time analysis of the resource usage, which in turn enables timely and optimal decision-making on handling, supply, delivery, storage and other asset management tasks. Various types of sensing devices, such as GPS devices and passive RFID (Radio-Frequency Identification) tags, are applicable with the sensor networks used for asset monitoring.

Building Monitoring
The recent attempt aiming at optimizing the energy performance of the buildings by deep sensing of the building conditions, dubbed BIM (Building Information Modeling)[2], heavily relies on the sensor network technology. With BIM energy tools enabled by sensing networks, one can monitor, e.g., the temperature and lighting conditions in the building, and accordingly regulate the heating and cooling systems, ventilators and lights dynamically for best energy performance [8]. Also as a safety tool, building sensor networks can detect and report threats, such as existence of the biological agents in the environment as well as physical intrusions.

Automotive
With the new standards such as Dedicated Short-Range Communication (DSRC) designated for vehicle communications, in near future cars will be able to communicate information to each other and to the roadside infrastructures. With this capability, while in traffic cars can form a so-called vehicular sensor network, where each car equipped with sensing devices (e.g., camera, thermometer, etc.) acts as a mobile sensor node. In a vehicular sensor network, cars can share information and analyze the aggregate information about the road conditions, congestions, nearby emergencies, etc., for applications such as collision prevention, congestion avoidance and flow optimization [9].

Healthcare
Sensor networks can effectively improve the accuracy of the patient care and, consequently, the safety of the patients when they become physically incapacitated and require immediate medical attention [10]. Sensor networks allow this by enabling close and automated monitoring of the patient's vital signs. When monitoring is coupled with real-time analysis of the signs, the sensor-enabled healthcare system can alert the right person at the right time to attend to the patient. Such healthcare systems are applicable both at homes of the elderly and at the hospitals.

Industrial Monitoring
Sensors can be used to monitor industrial processes for safety as well as manufacturing optimization [11]. One can also deploy sensors to monitor the condition of the industrial equipments for preventative maintenance and also safety of the operators. Wireline sensors have been in use for a long time in various industry sectors such as oil companies (both upstream and downstream) and chemical plants. Wireless technology and inexpensive sensors has greatly facilitated and extended the use of the sensing networks for process and equipment monitoring, encouraging oil companies, e.g., to develop smart oilfields by equipping the oil wells and other assets with wireless sensors (see [12] for example).

FUTURE DIRECTIONS *

[2] Federal BIM Program. URL: http://www.gsa.gov/bim/

With the current trend, sensor networks are being applied with increasingly more complex, large-scale and distributed systems (e.g., the federal intelligent transportation system[3]). Such applications demand deployment of large-scale sensor networks and, accordingly, require fully decentralized solutions for sensor data management to achieve scalability.

DATA SETS *

- CENS data sets. URL: http://research.cens.ucla.edu/portal/page?_pageid=59,54414&_dad=portal&_schema=PORTAL
- Intel lab data set. URL: http://db.csail.mit.edu/labdata/labdata.html
- Precipitation data set. URL: http://www.jisao.washington.edu/data_sets/widmann/
- IHOP data set. URL: http://www.eol.ucar.edu/rtf/projects/ihop_2002/spol/

CROSS REFERENCES

Sensor networks, Continuous queries in sensor networks, Ad-hoc queries in sensor networks, In-network query processing, Data acquisition and dissemination in sensor networks, Data aggregation in sensor networks, Data storage and indexing in sensor networks, Data uncertainty management in sensor networks, Database languages for sensor network tasking

RECOMMENDED READING

[1] Estrin, D., Govindan, R., Heidemann, J., Kumar, S. Next century challenges: Scalable coordination in sensor networks. *In Proceedings of the International Conference on Mobile Computing and Networking (MOBICOM)*, Seattle, August 1999.

[2] Bonnet, P., Gehrke, J., Seshadri, P. Towards sensor database systems. *In Proceedings of the International Conference on Mobile Data Management (MDM)*, Hong Kong, January 2001.

[3] Yoon, S., Shahabi, C. The Clustered AGgregation (CAG) technique leveraging spatial and temporal correlations in wireless sensor networks. *ACM Transactions on Sensor Networks (TOSN)*, Volume 3 , Issue 1, March 2007.

[4] Sharifzadeh, M., Shahabi, C. Utilizing Voronoi cells of location data streams for accurate computation of aggregate functions in sensor networks. *GeoInformatica*, Volume 10, Number 1, March 2006.

[5] Cerpa, A., Elson, J., Estrin, D., Girod, L., Hamilton, M., Zhao, J. Habitat monitoring: Application driver for wireless communications technology. *In Proceedings of the SIGCOMM Workshop on Data Communications in Latin America and the Caribbean*, Costa Rica, April 2001.

---

[3] Federal ITS Program. URL: http://www.its.dot.gov/

[6] Nemeroff, J., Garcia, L., Hampel, D., DiPierro, S. Application of sensor network communications. *In Proceedings of the Military Communications Conference (MILCOM)*, Virginia, October 2001.

[7] RFID Journal. URL: http://www.rfidjournal.com/

[8] Schmid, T, Dubois-Ferrière, H., Vetterli, M. SensorScope: Experiences with a wireless building monitoring sensor network. *In Proceedings of the Workshop on Real-World Wireless Sensor Networks (REALWSN)*, Stockholm, June 2005.

[9] Lee, U., Magistretti, E., Zhou, B., Gerla, M., Bellavista, P., Corradi, A. MobEyes: Smart mobs for urban monitoring with a vehicular sensor network. *In IEEE Wireless Communications*, Volume 13, Issue 5, October 2006.

[10] Ho, L., Moh, M., Walker, Z., Hamada, T., Su, C. A prototype on RFID and sensor networks for elder healthcare. *In Proceeding of the 2005 ACM SIGCOMM Workshop on Experimental Approaches to Wireless Network Design and Analysis*, Pennsylvania, August 2005.

[11] Chong, C., Kumar, S.P. Sensor networks: Evolution, opportunities, and challenges. *In Proceedings of the IEEE*, Volume 91, Issue 8, August 2003.

[12] The Center for Interactive Smart Oilfield Technologies. URL: http://cisoft.usc.edu/

[13] Culler, D., Estrin, D., Srivastava, M. Sensor network applications (Cover Feature). *IEEE Computer*, Volume 37, Issue 8, August 2004.

[14] Zhao, F., Guibas, L. Wireless Sensor Networks: An information processing approach. First Edition, Morgan Kaufmann Publishers Inc., ISBN 1-55860-914-8, July 2004.

[15] Center for Embedded Networked Sensing. URL: http://www.cens.ucla.edu/