Using Knowledge-based Information Systems to Support Management of Wireless Sensor Networking Systems

Sheng Zhang *zwxzs168@126.com*
School of Information Engineering, Nanchang Hangkong University
Nanchang, China

Xiao-dong Liu *technology12@163.com*
School of Information Engineering, Nanchang Hangkong University
Nanchang, China

William Wei Song *wso@du.se*
Business Intelligence and Informatics, Dalarna University
Borlänge, Sweden

Abstract

Currently, researches on Wireless Sensor Networks (WSN) mainly focus on how to efficiently gather sensing data from WSN, but little attention has been paid to how to effectively manage the large amount of collected sensing data. Information Systems (IS) are appropriate tools for data input, storage, processing, and output. Knowledge Management (KM) further transforms useful information into domain knowledge for decision making by domain experts. In this paper, we propose an approach to management of sensing data and transformation of sensing data into valuable knowledge using knowledge-based information systems. Firstly we propose a framework for knowledge-based information systems which deals with internal and external information using intelligent agents to generate domain knowledge with KM methods. Then we definite a model of knowledge-based information system for WSN to implement intensive sensing data storage, knowledge discovery, statistical analysis, sharing, inquiry, decision support. Finally, a prototype system is developed and tested for the aforementioned ideas.
Keywords: WSN, Information System, Knowledge Management, Intelligent Agent

1. Introduction

A wireless sensor network (WSN) is an autonomous network system that is usually laid in an unattended area, and can complete monitoring tasks. It is composed of a large number of tiny sensor nodes to monitor physical and/or environmental conditions, such as temperature, sound, and pressure. Wireless sensor node is low-powered device equipped with a processor, a memory, a power supply, a transceiver, and one or more sensors, in some cases, with an actuator. A WSN, as an IT hotspot technology, has a significant impact on human being lifestyles in the 21st century, following the Internet technology [8]. Wireless sensor networks link the virtual world of information with the objective physical world, and change the interactive way between humans and environment. WAN has very broad application prospects. It can be widely used in military, environmental monitoring, health care, traffic management and commercial applications and other fields [4].

With applications of WSN in various fields, enormous sensing data are generated constantly. Consequently, many issues occur, for example, how to share effectively the huge sensing data, how to maintain so many WSNs working normally, and how to find out useful information for decision making.

The “Global Sensor Networks (GSN)” project [1] comes true to share sensor data in wide range with middleware technologies. And it offers virtual sensors to integrate sensor network data through plain SQL queries over local and remote sensor data sources. The GSN mainly focus on integration and sharing of heterogeneous and very large scale sensor data, while WSN is only a kind of tools for gathering sensor data in the GSN project. The literature [5] proposed middleware architecture which is Service Oriented (SOA) for normal node and gateway node in WSN. The knowledge management (KM) and ontology are used to monitor and take decisions. It focuses on how to design the middleware architectural and the communication protocol between components at the node level.

Information system (IS) is used to enhance business processes through information technologies. IS usually involves a number of processing steps including analysis, design and implementation of IT systems and applications to support business functions [10]. A knowledge management system (KMS) is an information technology (IT) based system, which is developed to support and enhance the processes of knowledge creation, storage, retrieval, transfer, and application [9]. KMS can help an organization's management strategy to become more competitive in a rapidly changing environment [6].

In order to effectively manage a large amount of sensing data of WSN, we propose a knowledge-based information system for WSN (KIS4WSN) which is composed of three components: Wireless Sensor Networks (WSN), Knowledge Management (KM), and Information System (IS), see Fig. 1. Meanwhile, we can use the intelligent agent technology to gather sensing data, provide services for different users in KIS4WSN.

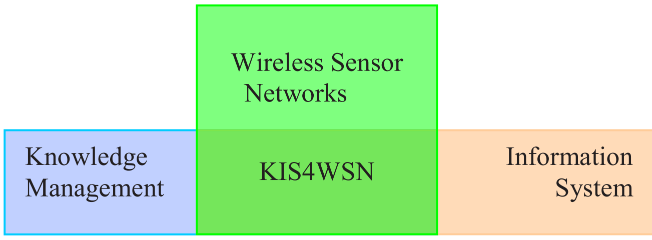

Fig. 1. The KIS4WSN system uses WSN to collect data, IS to store and manage data, and KM to extract and analyze data, and yield controls on WSN

The remainder of this paper is organized as follows. Section 2 describes how to design architecture of a knowledge-based information system for WSN that could support the management of a WSN, as well as supporting knowledge, experience and decision-making. Section 3 introduces the key information processes and technologies for system implementation. Section 4 shows a prototype system and a brief evaluation. And section 5 concludes overall paper and lists future work.

2. Methods

In order to develop the KIM4WSN, we consider a working framework consisting of topologic structure of a WSN, a set of functions built on the WSN, and a collection of implementation methods applied to the functions (operations). In this section we introduce a conceptual model for the basic concepts of wireless sensor network structure in a formal representation, relations among the WSN states, functions, and implementation methods. We also propose a structural system to indicate various working components used to realize the model.

2.1. Concepts

Definition 1 (**WSN**) A WSN is a directed graph with a time dimension, denoted as

$$\mathrm{N} = \{V, E, \mathrm{t}\} \tag{1}$$

where $\mathrm{V} = \{v_1, v_2, ..., v_n\}$ represents the set of nodes, $\mathrm{E} = \{(v_i, v_j) \mid v_i, v_j \in V\}$ represents the set of edges, and t is a time at which the network has a state S, which will be defined later. We assume that the WSN N can change its state from time t_1 to time t_2.

Definition 2 (**Connected Network**) Suppose that N is a WSN. N is **connected** for any two nodes v_1 and v_2 ($v_1, v_2 \in V$) in N, if there is at least one reachable path. If there are k paths, N is called **k-connected**.

Definitions 3 (**Sub-WSN**) Suppose that $N_S = \{V_s, E_s, t\}$ and $N = \{V, E, t\}$ are two WSN's. N_S is defined to be a sub-WSN of N if $V_S \subseteq V$ and $E_S \subseteq E$ at time t. Let $N_i = \{V_i, E_i, t\}$ and $N_j = \{V_j, E_j, t\}$ are two sub-WSN's. N_i and N_j are defined to be **independent** from each other (independent sub-WSN's) if $V_i \cap V_j = \phi$, and for any $v_1 \in V_i$ and $v_2 \in V_j$, there exists no edge (v_1, v_2).

Definition 4 (**Functions**) $F = \{F_1, F_2, ..., F_n\}$ is a set of functions defined on the WSN N, where, F_i is a kind of operations applied to various components, including nodes, edges, and sub-network, and the whole network, of N. Usually, there are three categories of operations i.e. the operations for the nodes (e.g. node positioning and storage management), the operations for the edges (e.g. status monitoring and coverage control), and the operations for the parts (sub-network) or the whole network (e.g. network routing, data fusion, time synchronization, network security, and topology control).

To develop a conceptual model for the WSN4KIS, we propose an important concept here, which is the state of a WSN N. A state of a WSN N is associated to the time dimension t, as we define in Definition 1 (WSN). The basic concept for the sate of a network is whether a node, an edge, or a part of N is occurring in the network N. The node state includes the node physical state and node network state. The node physical states are composed of the node physical characteristics, e.g., the radius of the communication, the residual energy, storage capacity, processing capacity, position coordinates, and so on. In this paper, the node network state indicates whether a node is capable to communicate with other nodes.

Definition 5 (**Network State**) A set of the nodes state and edges state at a moment for a network,

$$S_t(N) = \{S_t(V), S_t(E)\} \tag{2}$$

where $S_t(V)$ indicates the status of nodes in the network at time *t*, $S_t(E)$ represents the status of edges in the network at time *t*.

The node state includes the node physical state and node network state. The node physical states are composed of the node physical characteristics, e.g., the radius of the communication, the residual energy, storage capacity, processing capacity, position coordinates, and so on. In this paper, the node network state indicates whether a node is capable to communicate with other nodes.

The state of node v_i can be expressed as follows (at the time *t*).

$$S_t(v_i) = \begin{cases} 0 & node\,disable \\ 1 & node\,normal \end{cases} \tag{3}$$

The state of edge is that there is available communication between two nodes when the nodes are normal. The edge state from node v_i to node v_j at moment *t* can be expressed as:

$$S_t(e_{ij}) = S_t(v_i \rightarrow v_j) = \begin{cases} 0 & not\,communicating \\ 1 & is\,communicating \end{cases} \tag{4}$$

Definition 6 (Function Implementation): a set of the different implementation methods for a function F_i.

$$I_i = \{I_{i1}, I_{i2}, ..., I_{im}\} \tag{5}$$

where I_{ij} ($1 \le j \le m$) represents the *j*th implementation method of *m* different methods for a function F_i.

In general, a function in WSN can be implemented in many methods. For example, network routing which is an important function in WSN can be divided into flat-based routing, hierarchical-based routing, and location-based routing depending on the network structure [2]. There are many implementation methods for three above mentioned three kinds respectively. More details please read the conference [2].

2.2. Relations of Networks, Functions and Implementations

For different application scenarios (e.g., wildlife monitoring, military detection, health monitoring, medical monitoring, traffic monitoring, etc.), the WSN needs different network model. The structure, setting, information processing mode, real-time, security requirements of WSN are different, so there are different functions need to deal with the particular application networks. Meanwhile the implementation of a function is different in different kind WSN application.

For the convenience of dealing with complex application requirements, we construct three sets to store all kinds of WSNs, all functions, and all implementations. They are called the set of network of WSN (N), the set of function (F), and the set of implementation (I).

A WSN N_i ($N_i \in N$) maybe include several functions F_1, $F_2,...,F_m$ ($F_i \in F$ $(i=1,2,...,m)$), while a function F_i must be implemented using several different methods or algorithms I_{i1}, $I_{i2},...,I_{in}$ ($I_{ij} \in I$ $(j=1,2,...,n)$). So it exists a map between the WSN set N and the function set F, and another map between the function set F and the implementation set I. The relations of N, F and I is shown in Fig. 2.

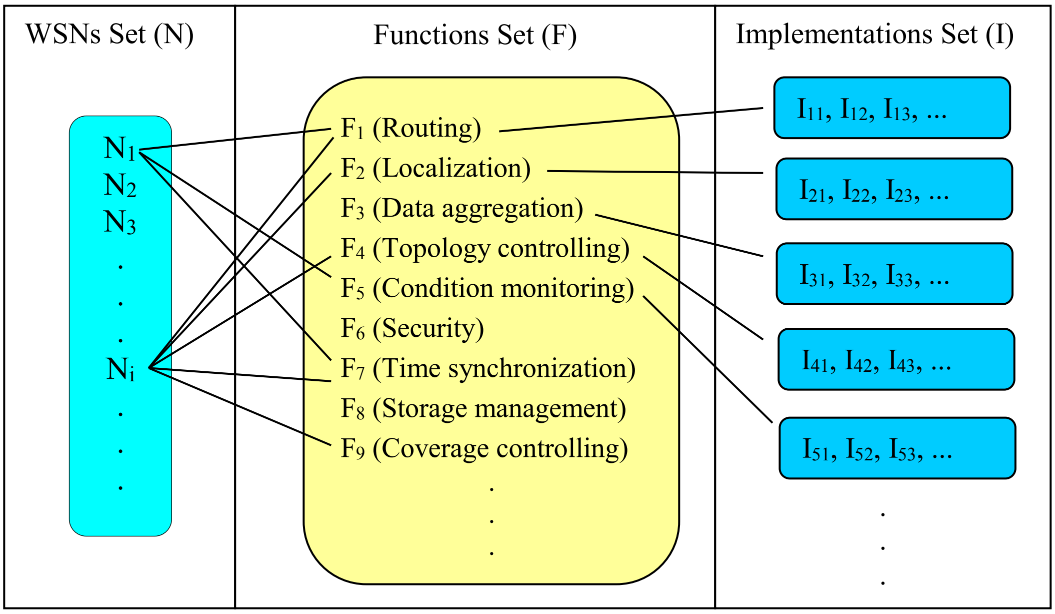

Fig. 2. Relations of WSNs, functions and implementations

2.3. An Example of Function: Routing

The following brief description of an example shows the network routing conception and one of the basic implementation methods.

A routing is the process of forwarding a packet of data from a source node to a destination node. Routing algorithm can be briefly described as follows:

```
Algorithm Routing
Input  N, v_s, v_d  //network, source node, and destination node
Find the path set P = {p_1, p_2, ..., p_n} from the node v_s to node v_d;
Select the optimal path p from set P;
Output p;
```

There are a lot of implementation algorithms as described above for network routing. The classic algorithm is gradient-based routing, for example, sensing data between the network nodes forwarding process follows the algorithm shown below [7].

```
Algorithm basic-gradient-routing   // Forwarding process
Message forwarding on node n:
  Reception of packet p
  if ( p.depth > n.depth ) && ( p.seq ∉ n.seqlist) then
     if ( n ≠ sink ) then
        p.depth = n.depth ;
        n.seqlist ← p.seq ;
        broadcast packet p ;
     else
        Process packet p ;
     end if
  else
     Drop p
  end if
```

2.4. System Architecture

We propose the architecture of KIS4WSN which is shown in Fig. 3. It includes five layers, i.e. user request analysis layer, interaction layer, knowledge management layer, information processing layer and data handling layer.

User request analysis describes user requests for a variety of applications of WSN. Such as, real-time monitoring, web browsing sensing data, information query, statistical analysis, data mining, trend analysis, decision support, and so on.

Interaction is the information exchanging or service interface between the KIS4WSN and the users, is carried out by interface service agents. The interface service agents response user's requests, analyze the requests, and patch related function agents to execute the tasks, then collect the results from function agents, and finally return the results to the users.

Knowledge management is a result of processes including synthesis, filtration, comparison and analysis of available information by the domain experts. In KIS4WSN, knowledge management includes acquisition and storage of knowledge, creation and representation of knowledge, discovery and application of knowledge, inference and sharing of knowledge. It is supported by domain knowledge, empirical knowledge and domain experts.

Information processing is the process of raw data into meaningful information. In our information system, information processing includes two parts. The first part is the information processing for current wireless senor networks, and the other part is information processing for historical sensing data. For current WSNs, there are many corresponding functions of network operation, such as, network routing, node positioning, data fusion, time synchronization, security control, topology control, condition monitoring, information collection, storage management, coverage control, data forwarding, data query, statistics and analysis, and so on. For historical sensing data, there are information index, data sorting, trend analysis, data statistics, abnormity detection, data selection and filtering, etc.

Data handling stores and provides all kinds of raw data, information, algorithms and knowledge. It includes sensing data, network information, operating functions, implementation algorithm, meta-knowledge, conceptual knowledge, content knowledge, reasoning rules, etc.

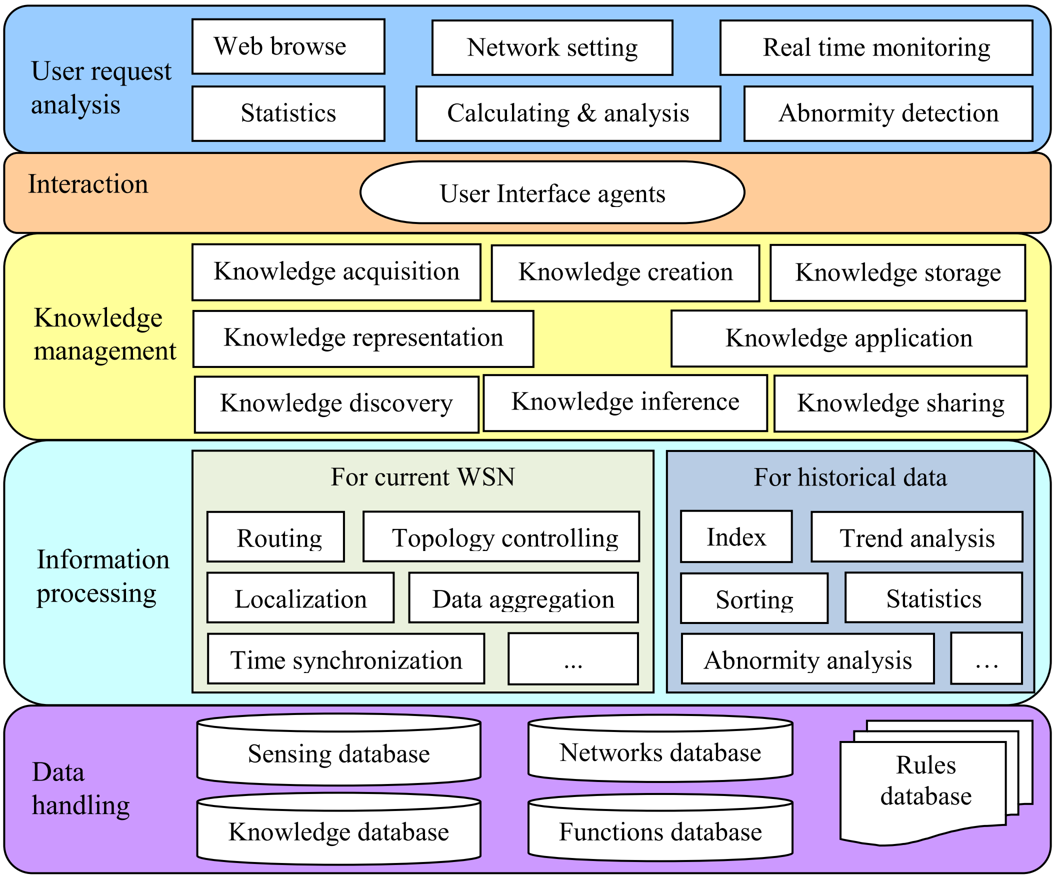

Fig. 3. The architecture of KIS4WSN

3. System Implementation

According to above ideal of the architecture, we describe the implementation in three aspects: the data organization, the main information processing, and knowledge acquisition method.

3.1. Related Databases

All kinds of data, information, knowledge and methods need to be stored in the KIS4WSN, so it includes the following databases:

Wireless sensor networks database contains all kinds of description information for WSN of different application scenarios. Such as military reconnaissance, wildlife monitoring, environment monitoring, health care monitoring, traffic monitoring, forest fire monitoring, and bridge health monitoring.

Functions database stores the various processes and operations functions for all types of wireless sensor networks. For example, network routing, node positioning, data fusion, time synchronization, security control, topology control, condition monitoring, information collection, storage management, coverage control, data forwarding, information query, statistics reports, and trend analysis.

Implementations database manages a set of different implementation methods of the functions for different wireless sensor networks. For example, storage management includes main three kinds of methods as external storage, local storage, and data-centric storage.

Sensing information database stores all kinds of historical data collected from wireless sensor networks, such as temperature, humidity, light, pressure, vibration, speed and acceleration for each node at different time period.

Knowledge (rules) Library manages the various knowledge or rule for agents to judge and reason. Such as domain knowledge, empirical knowledge, rules knowledge, etc. For example, some rules can be

• **if** temperature is higher 60 **then** sound alarm;

• **if** results of user query are in current database **then** return for user **else** gathering the data from WSN and dealing with them according to user requirements, meanwhile storing results into current database.

3.2. Information Processing

User Requests / Service Process

Different users have different needs and send different requests. The interface agents should be able to analyze user requests with the support of the knowledge base and rules library, and select the suitable type of WSN, confirm the requested operation functions according to the analysis results, then dispatch different implementation agents to complete related functions. The implementation agents will return the results to the interface agents after finishing the tasks. The final results will be sent back to the requesting user by the interface agents. Therefore, these processes require collaboration of multiple agents. The process is shown as Fig. 4.

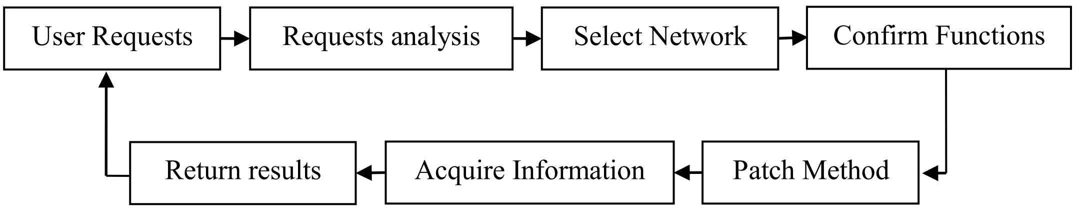

Fig. 4. User requests / service processes

Sensing Data Forwarding Process

The sensing data forwarding process is that the monitoring data of hotspots in the form of packets transmit to the Sink node by a kind of routing algorithm. Satisfying different user's needs, Sink node usually send the collected monitoring data to PC by serial communication connection. In the same time, the monitoring data can be used for real-time monitoring, and stored in the database (or sensing information document) for history query or data analysis in future. The process is shown as Fig. 5.

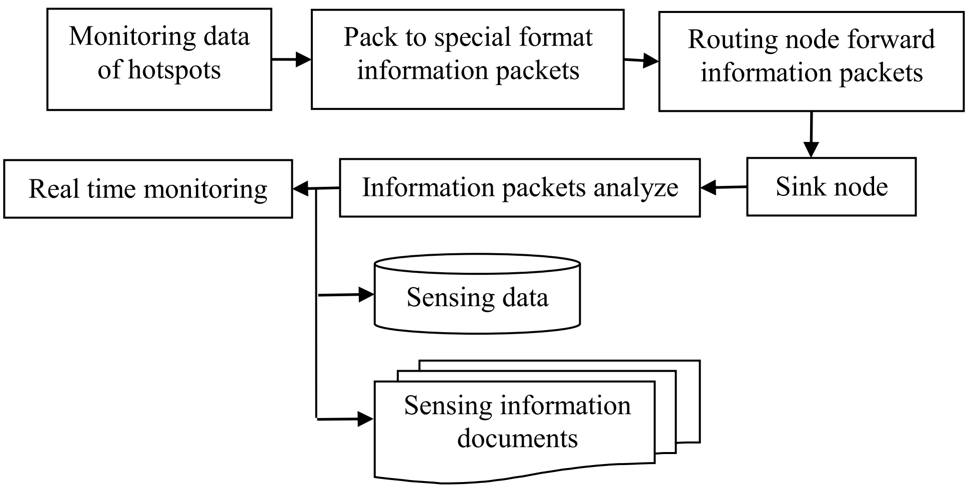

Fig. 5. Forwarding process of sensing data

XML Format Conversion

In order to facilitate information distribution and query on the Web, we need to convert the packets information into XML format. The process which sensing information packets convert into XML format is shown in Fig. 6. The XML analyzer (e.g. SAX) converts sensing data streams into XML data streams with XML Schema. It can offer a variety of services on the Web by related operations (e.g. queries) to XML data streams.

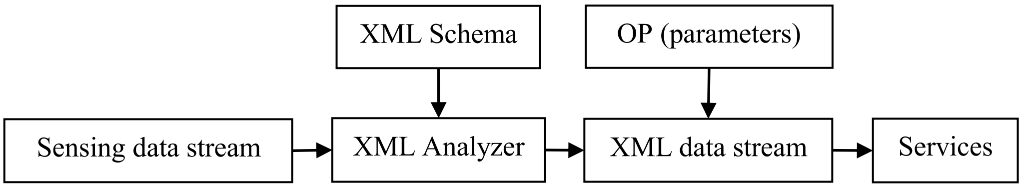

Fig. 6. Process for sensing data converting to XML format

3.3. KIS Model Based on Multi-agents

After putting forward the architecture of KIS4WSN, but there are huge information, and complex operation or functions, now the question is who can act as the important role to deal with the complex business? We select the agent technology.

In computer science, an intelligent agent is an autonomous entity which observes and acts upon an environment and directs its activity towards achieving goals using learning or knowledge [3]. WSN is a distributed system too. The nodes in WSN own the ability of solving problem independently, and have the characteristics of self-organization. These features are very similar as multi-agent system, so the agent technology is applied to WSN is a natural thing to do.

From an intelligent agent's point of view, the KIS means knowledge acquisition, processing and use for rational decision-making, choosing the best action and generating new knowledge. Therefore, a multi-agent system (MAS), which consists of multiple interacting intelligent agents, will be needed to solve problems that are too difficult or impossible for an individual agent. A proposed KIS model which combines KM and MAS is shown in Fig. 7.

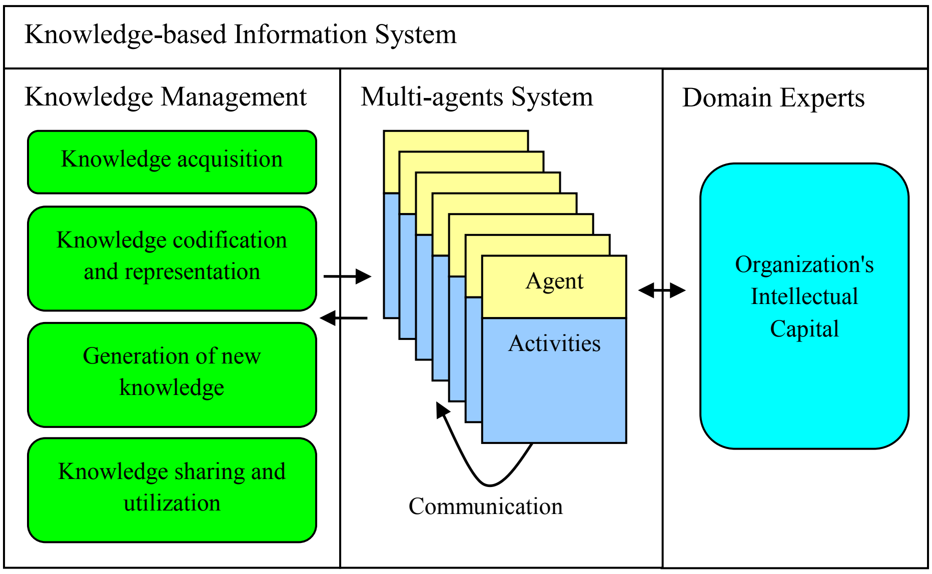

Fig. 7. KIS model based on multi-agents

The conceptual framework of a KIS based on multi-agents consists of three main parts: a KM, a MAS and domain experts for business process support. The KIS is an integrated set of technologies, hardware and software, to provide knowledge acquisition, storage, processing, retrieval and representation. The KM is usually supported by AI techniques. The purpose of adding KM into the KIS is to identify intellectual capital of the organization and organize that knowledge to make it easily accessible and applicable. The MAS is a physical or virtual environment where intelligent agents may communicate with each other for effective. The domain experts provide intelligent support.

There are main two kinds of agents in KIS4WSN, one is interface agents, and another is function agents. The typical interface agents include: agents between users and IS, agents between PCs and WSNs, and agents between functions and database. The function agents include all kinds of operation functions to database or WSN. Meanwhile the correlative agents can complete the same goal cooperation each other.

4. A Prototype System and Evaluation

According to the above design ideas, we have developed a prototype system called "Wireless sensor network data gathering and analysis system". The prototype system is developed using Visual Studio 2005, and the database management system selected Oracle 9g.

The main functions include system management, network status, data management, real time monitoring, and help information, see Fig. 8.

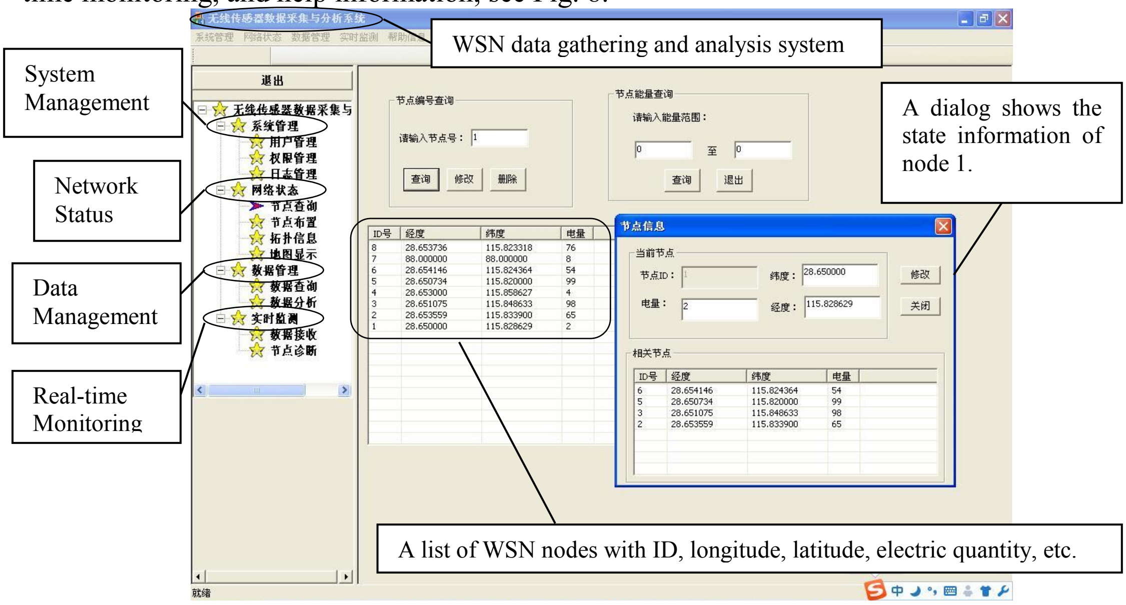

Fig. 8. Nodes status query

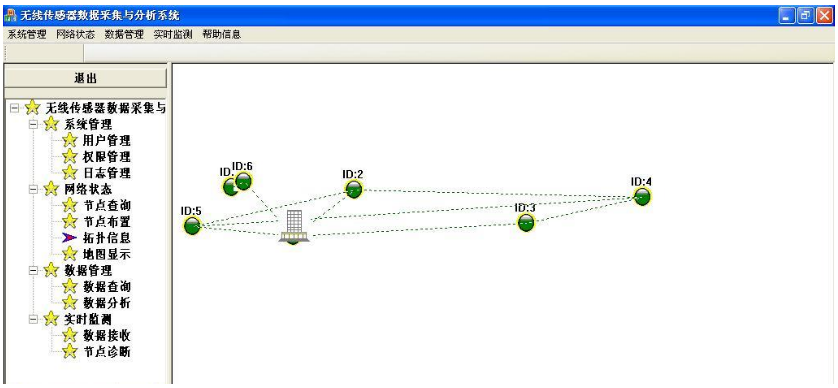

Fig. 9. Nodes topology information

System management main includes user management, privilege management and log management. Network status includes node status query, node layout, topology information and map displays. Fig. 8 is a snapshot of nodes status query. Fig. 9 is a part of the screenshot of nodes topology information. Data management includes historical data query and data analysis. Real-time monitoring includes data receiving and node diagnostics.

We focus on gathering sensing data and optimizing performance of WSN now, although a prototype system has developed. In the prototype system, it is short of knowledge management and sharing information in Web, and knowledge discovery and trend analyses are insufficient.

5. Conclusions and Future Works

Wireless Sensor Networks (WSN) has become a hot research topic recently and researchers' interests have been focused on how to improve the performance of nodes and networks and efficiently gather sensing data from WSNs. However, little attention has been paid to efficient management of the huge sensing data that are gradually formed, let alone effective use of these data. Meanwhile, different WSN application scenarios may require specific wireless sensor networks, which, apparently increases the complexity of the operation functions placed on the networks and their massive sensible data as well. In this paper, consequently, we put forward a knowledge-based information system solution to these problems in WSNs, which applies the information systems approach (IS) to efficiently manage the huge sensing data and exploit knowledge management (KM) systems and multiple agent systems (MAS) to turn information into knowledge.

In this paper, we introduced briefly related conceptions, including WSN, KM and IS, to address the issues of how to manage gradually increasing WSN sensing data, and consider an ideal knowledge-based information system for WSN data management. We proposed a system architecture for KIS4WSN, and a number of key technologies for implementation guidance. We also discussed how to develop a system prototype of KIS4WSN, and its interfaces to accommodate required functions placed in the networks and data. However, there are still shortages in this prototype system, which we will try to overcome in our future work. In the following, we consider a more concrete idea of how these problems can be solved in the future.

First, the system intelligence needs to be enhanced, by incorporating into the system, not only using multi-agents, but also adding further data analysis methods with artificial intelligence technologies, such as artificial neural networks (ANN), pattern recognition, and generic algorithms. These added functions can be considered services, which are flexibly attached to our system (viewed to be a platform).

Second, the application area of system can be broadened. The prototype system, proposed here, is an experimental system for the WSN research. We try to enable it to adapt to different application scenarios, e.g. wildlife monitoring, environment monitoring, health care monitoring, traffic monitoring, forest fire monitoring, bridge health monitoring, and other fields. Recently we explore to use this idea at a project proposal, in which patients can be fully monitored when they are at home while doctors and nurses are still able to follow the patients' situations before and after taking medication.

Third, the system functions can be further improved. For example, the system can show nodes of WSN on a map with GIS techniques, locate the position of a mobile sensor with GPS, and use many apps from mobile phones, which take immediate measures of the WSN data when timely processing of these data is critical.

Finally, we also intend to explore whether a sound foundation for routing algorithms for wireless sensor networks could be established – a so called optimization algorithm could be further discussed based on 1) the structure (deep structure and whose components at different layers) of WSN nodes and networks (graphical partitioning and clustering), 2) the interdependencies between nodes, nodes' components, and connections, and 3) the probability of energy use of nodes, and transitions, and data accuracy.

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