Wireless Sensor Networks for Cultural Property Protection

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Abstract

Wireless sensor network technology has been proven to have a strong impact on our daily life from many real applications. In this paper wireless sensor networks for cultural property protection are introduced. We deployed wireless sensor networks in Bul-guk-sa Temple, which is one of the most important UNESCO cultural property sites in Korea. This paper presents our wireless sensor network system for monitoring and protecting cultural property from the aspect of application design to network system management.

1. Introduction

Advances in wireless communication and embedded software technology have led to successful adoption of wireless sensor networks in various applications. Some of such works include wireless sensor networks for environment and habitat monitoring, healthcare applications, traffic control, military and disaster management [1-5].

In addition to traditional applications, wireless sensor networks can be used to protect cultural property. In order to preserve the cultural property in a good condition, it is important to continuously monitor the surrounding environment of that property. This ensures that administrators can react properly by detecting any change or damage immediately.

Inspite of such requirements for cultural property protection, setting up any fixed structure with power lines and communication cables is not allowed in precious cultural property sites. In this sense, wireless sensor networks which do not require infrastructure can be used as ideal solutions for cultural property protection system.

Bul-guk-sa Temple is the world's cultural property as designated by UNESCO. We developed wireless sensor networks for monitoring and protecting cultural artifacts in Bul-guk-sa Temple. Our wireless sensor networks have two objectives: 1) periodic environmental information collection to monitor any changes in wooden structures, and 2) detecting fire outside the temple's surrounding forest. A forest fire would be fatal to the wooden temple. The conceptual cultural property management system is illustrated in Fig. 1.

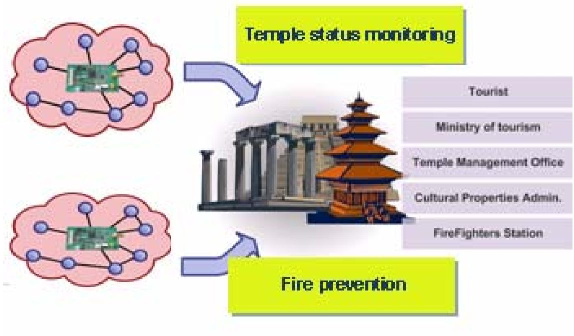


Fig. 1. Cultural Property Management

To meet the requirements of the wireless sensor network for cultural property protection we collect diverse physical information including temperature, humidity, light, pressure, flame and carbon monoxide (CO) data from the surrounding environment. A software system that utilizes sensor data on top of our ANTS sensor network operating system [2] and ANTS series of sensor node hardware was developed.

In this paper we report our experience of running three separate wireless sensor networks which consist of a total of 32 wireless sensor nodes in the Bul-guk-sa temple for six months.

2. Sensor Networks for Cultural Property Protection

The wireless sensor network system for cultural property protection reveals several requirements to consider.

(1) Environmental information monitoring

There are many environmental factors that can cause harmful effects to the wooden cultural property. We continuously collect temperature, humidity and light inside temple.

(2) Automatic fire detection

The temple is surrounded by a dense forest, and it is not easy for people to monitor the occurrence of a fire.

The sensor network was developed to automatically detect fire and send an alarm to remote users.

(3) Lack of infrastructure

No power line and network cables, which are necessary to put other electronic instruments, are allowed because the temple area is strictly limited by the law.

(4) System reliability

Inspite of unreliability of wireless communications and limited resources of sensor node hardware, the sensor network has to be reliable enough for real applications. In addition, fire detection has to work even if some parts of sensor nodes operate abnormally.

(5) Battery lifetime

Sensor nodes have to run without battery changes once the system is deployed. It is not easy to access or replace them after deploying them because of restrictions. Therefore, battery lifetime was one of the most critical factors in our system design.

3. Wireless Sensor Network Design

Three wireless sensor networks are designed and deployed to monitor the environment of the temple. One network is installed at the temple precinct, and the others are deployed around the temple. The precinct sensor nodes gather information such as temperature, humidity, and pressure inside the temple. The outside sensor nodes are deployed along a path through the forest surrounding the temple to detect forest fires. We explain our design details below.

3.1 Sensor Network Hardware

The sensor node hardware that we use for this project is classified into two; precinct sensor node and perimeter sensor node. The precinct sensor nodes are used to gather and provide essential information such as temperature, humidity, and pressure in order to check conditions of wooden buildings. These nodes are located inside the temple, and send sensory data over a RF communication. The processor on the single board is an ATMEL ATmega128L 8-bit microcontroller which is used in tiny sensor nodes [7][8]. It has 128Kbytes of flash memory, a 4Kbytes SRAM, and a 4Kbytes EEPROM inside the processor. The RF transceiver is a Chipcon 2420 (CC2420)[9] which utilizes the 2.4 GHz frequency band. Three kinds of sensors are used: a temperature/humidity sensor; a pressure sensor; and a light sensor. Since such sensors require low power consumption, we can use a battery without external power supply.

The outside sensor nodes consist of separate processor boards and a sensor board with a 41-pin connector. The processor is an ATMEL ATmega128L 8-bit microcontroller, which is the same as the precinct sensor node. The RF transceiver is a Chipcon 1100[11] which is a low power true single chip UHF transceiver. It can easily be programmed and configured for operation at frequencies in the 300-348MHz, 400-464MHz and 800-928MHz bands. On the sensor board, multiple sensors for sensing temperature, humidity, pressure, light, flame and carbon monoxide (CO) are used. To alleviate the power requirements of the sensor and processor boards, a 4.5V 140mA solar cell is used together. Figure 2 and Figure 3 show our sensor nodes.

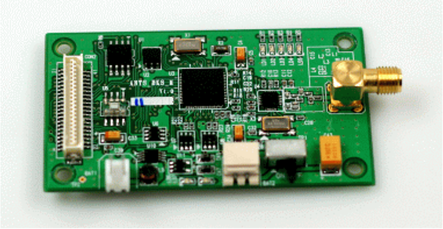


Fig. 2. Processor Board of Outside Sensor Node

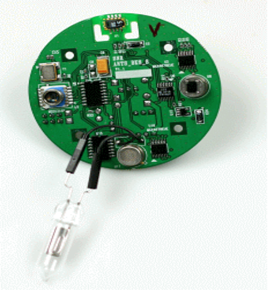


Fig. 3. Sensor Board of Outside Sensor Node

3.2 Data Gathering – software/network

As the underlying software framework for the system, ANTS EOS [2] (Evolvable Operating System) and ANTS network protocols including CSMA/CA based MAC and the ANTS-String routing protocol are developed. Since the temple is located at the center of a deep forest and the mission of the network is to detect and notify of fires that spread from outside the temple, the topology is decided to encircle the temple with connected nodes. To achieve reliability and fast delivery of the event data, we divided the network into two separated string-shape networks, each of which is assigned to different communication channels. Each network consists of 16 sensor nodes and has a dedicated base station that is connected to a base station using CDMA connections. Figure 4 shows our deployment.

To build the string topology, we assign a depth parameter to each node in advance. According to the depth, a node adds a child node as the one that has higher depth than it has. The depth does not need to be a unique parameter in the network. In cases where there exist nodes that have equal depths, the topology no longer becomes a string, but a DAG (directed acyclic graph) topology, but only one of the lower-depth nodes becomes the parent.

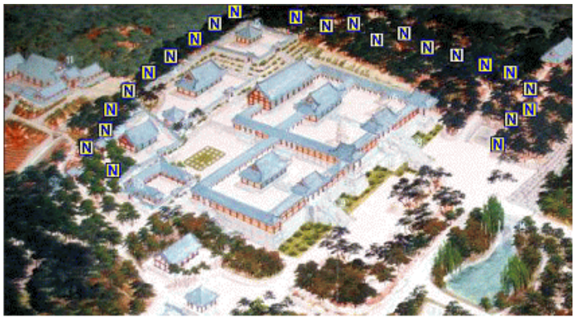


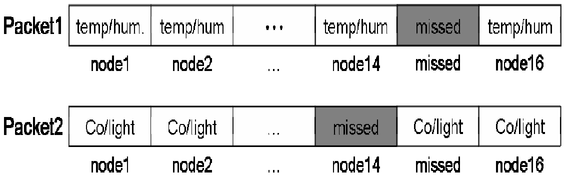
Fig. 4. Deployment map of sensor nodes. 'N' indicated locations of the sensor nodes in the monitoring GUI

The pure string topology makes the aggregation of data to be easy and efficient, but the reliability and robustness is rather weak due to the low redundancy of the alternative path. However, the DAG topology shows better robustness and reliability, but inefficient aggregation of data. We implemented both of the routing algorithms so that they can be selectively chosen depending on the situation.

In the pure string topology, nodes are synchronized by a pair of messages, the sleep message sent by the base station and the data packet initiated from the leaf node. Data transmission is initiated only by the leaf node. When it sends data to its parent, the parent aggregates its own data with the received one and then sends it to our parent again. This procedure is reactively and repeatedly performed until the aggregated data packet reaches the base station. If a node is in a default state so that it cannot participate in the communication, the node is excluded in the procedure after a few trials, and the sending node passes over the node in default and sends data to the next node (one-hop further), if it's in range. Discarded node is rejoined and retried in the next data gathering procedure.

On receiving the aggregation packet, the BS floods the network with a sleep message. The sleep message describes how long the nodes go to sleep and nodes receiving the message thus relay it and go to sleep immediately. Then, after a certain time, all nodes are awakened. To cope with a minor awaken timing gap, experimentally tuned delay is given. Finally, the leaf node that has been waked up initiates a new data gathering procedure by sending its data.

Our aggregation is a little different from that introduced in [10]. Our aggregation is defined as putting as much data into a packet as possible. The application packet size s is divided by the number of nodes n and the size in which a node can put its application data is thus bound to s/n. Thus, if the application data size is smaller than s/n, then we can gather all nodes' data with just one transmission. Otherwise, we need to send it more than once and a delay is required to avoid collisions. In our case, application packet sizes are 49 bytes and application sensing data are 6 bytes, we send them twice by fragmenting. Fig. 5 illustrates the packet structure.



Packet1	temp/hum.	temp/hum	···	temp/hum	missed	temp/hum
	node1	node2	...	node14	missed	node16
Packet2	Co/light	Co/light	...	missed	Co/light	Co/light
	node1	node2	...	node14	missed	node16

Fig. 5. Packet Structure

In the DAG topology, aggregation is not employed and all nodes send their data to the base station and also sleep and awake independently and individually. Thus, global synchronization is not needed. This scheme provides stronger connection to the BS by supplying several alternative paths and possible parents. However in terms of energy consumption, it is worse than the string.

3.3 Fire Detection

Our perimeter sensor nodes were deployed to detect fire automatically and give alarm to administrative organizations. A sensor node is equipped with 5 sensors including temperature, humidity, pressure, carbon monoxide and a flame detector. The reason for using multiple sensors to detect fire is to assure high fast responses and reliability. Different sensors have different fire detecting characteristics generally, and the operations are affected by diverse environments. In addition, it is important to minimize the dangers of false alarm from one type of sensor in a certain environment.

According to our experimental results, the flame detector can detect fire 50 meters away from the fire spot while sensor data such as temperature, humidity, and pressure can provide effective fire detection only at nearer distances. The detection of fire using carbon monoxide is effective if it is installed down wind. Although it is the most effective sensors under windy environments, it depends on the wind direction because the wind delivers the carbon monoxide to the sensor.

On the other hand, a flame detector has a limited detection angle, and it is difficult to determine the detected fire size and distance from the sensor. In addition, a flame detector can be easily affected by natural ultraviolet light, which can lead to a false alarm. The advantages of temperature, humidity and pressure sensors are that they can monitor the fire with relatively high accuracy, and they can continuously measure progress of the fire.

We employed voting based arbitration to judge fires from multiple sensor data. If the sensing value of a node satisfies the specific conditions of a fire, the node issues a certain number of votes. The number of votes is calculated so that a base station can judge whether there is a fire.

3.4 Base station using CDMA network

The base station is a gateway to the Internet. It collects sensing data and sends it to the server via CDMA network. The base station is composed of an embedded Linux board, a sink node, and a CDMA modem. The sink node and the CDMA modem are connected to the UART ports of the base station board. The sink node receives data from sensor nodes, and it sends them to Linux board. Then, the Linux board parses data and transmits it to the server via the CDMA network. CDMA modem has embedded TCP/IP stack. The board sends ‘AT’ commands to the modem and parses its response messages. After that, the board opens a socket to the server and transmits the collected sensing data.

The software of the base station board consists of main routine and two threads for serial communications. One of the three is for the sink node while the other is responsible for communications with the modem. Also, the main routine enables a watchdog timer after every single serial communication to protect the system from unexpected faults.

3.5 Remote Monitoring System

Wireless sensor network for cultural property protection consists of three sensor networks. One is deployed on the precincts of a temple, and uses the 2.4 GHz RF frequency board to communicate. The others are deployed along the perimeter of the temple to detect a forest fire. They use the 900 MHz RF frequency board, and support multi-hop networking.

The 2.4 GHz sensor network and 900 MHz sensor networks use different message formats for communicating and producing sensory data in different formats. To guarantee transparency in the sensor data format, we used the dynamic link library which can be used by the application to connect to the wireless sensor network. The library receives sensory data from the sensor networks and parses the data into the predefined structure format to applications. Because the library provides a connection to the base station and complex sensor data format is encapsulated, the application embeds the library into the application to use our wireless sensor network without know network connection or sensory data format.

To utilize collected data from wireless sensor network, the service architecture consists of a GUI application, database, a web server and a web logger. The GUI application is used by the cultural property administrators. This application provides a real-time display that shows what is going on with the sensor network. If an abnormal event occurs, the application will notify the administrator of what happened.

3.6 Energy Control

In case of the network inside the temple, since its main goal is preventing erosion of the wooden building by monitoring temperature, humidity, and illumination, a 20 minute cycle sensing period was used. We applied a sleep and wake up mechanism for CPUs, RF modules, and sensor modules so that when sensor nodes are not sensing, they change their status to the sleep state. Later, when they wake up, they sense once, and then go back to sleep. Battery consumption for 5 seconds of sensing and 20 minutes of sleep are 28.65mA and 0.42mA, respectively. Therefore, without considering environmental effects, we can compute the expected life time of the sensor nodes. With the 6600mAh capacity batteries, we can roughly expect 17 months life time without changing its battery.

(1) $6600 / (0.42 * 1200 + 28.65 * 5) / 1205 / 24 / 30 \cong 17$

In the case of the networks outside the temple, since their main purpose is detecting fire in a short time, energy control is a more critical issue. The sensor nodes should report their sensory data more frequently because fire can spread in a short time. In addition, some sensors, such as the flame detection sensor and the carbon monoxide sensor, require higher power.

To alleviate the power problem we employed solar cells with sensor nodes. Moreover, we set the duty cycles for flame sensors and carbon monoxide sensors so that we divide the wake up period with the small duty cycle, and only enable those sensors for 250msec in 2 sec duty cycle. After this 2 seconds duty cycle, sensor nodes change their status to the sleep mode and have their sensors, CPU, and RF module turned off for 8 seconds. In the 8 seconds sleep and 2 seconds duty cycle, the average battery consumption is 1.68mA and

12mA respectively. With 15400mAh capacity batteries, we can roughly expect 5 months life time.

(2) 15400 / (1.68*8+12*2) / 10 / 24 / 30 = 5.780781

However, since we have a solar cell, the batteries of the sensor node can be recharged continuously. The average energy consumption of the sensor node per day is around 300W. If the weather is sunny throughout the day, the solar cell can recharge 2205W. Therefore, we can maintain the perimeter sensor network without concerned about the battery lifetime.

4. Deployment and Evaluation

The wireless sensor network for cultural property protection was deployed and evaluated in Bul-guk-sa temple from September 2006 to February 2007. From our experience, the primary difficulty was battery problem. Since multiple sensors were utilizing power in each node, consumption was high. Furthermore, solar-cells were not as effective as we expected. This was because the forested environment with tall trees prevents the solar cell from being exposed to direct sun light for long hours. Consequently, the lifetime of the networks was shortened and we solved this problem by adding sleep/wakeup. The next problem was installation difficulties in real fields. Because of the importance of the cultural property, the law did not allow us to setup any small support poles, so we chose to mount our sensor nodes on a tree. As a result, this affected the efficiency of the solar cell by blocking out the sun.

Fig. 6. A deployed sensor node on a tree

Another difficulty came from the communication frequency regulation. Because radio frequency for the wireless sensor network is not yet defined clearly by the government, the perimeter sensor network was initially configured to 433MHz, but had to be changed to 900MHz later to meet the regulation.

To verify our wireless sensor network system, we tested fire detection with sensor nodes from varying distances. We maintained the size of the flame at about 30-70 cm, and the tests were repeated in different environments. As shown in table 1, a flame sensor is the most reactive so it can generate an event about 62 meters away from the fire. The carbon monoxide sensor can detect fire about 14 meters away. However the distance is easily varied depending on the direction of the wind. Temperature, humidity and pressure sensors were not sensitive until fire came very close to the location.

Fig. 7. Experiment on fire detection

Sensor	Reacting Distance(Average)
Carbon monoxide	13.7m
Flame	62.3m
Temperature	1.5m

Table 1 fire detection

Fig.8 shows the experimental result of a precinct sensor node for the last 6 months which the sensor node sensed the ambient environment every 10minutes. The upper graph is the temperature log during the period and the lower one is the log of the remaining battery-level during the same period. The temperature is varied from -9 to 24°C and the remaining battery level is reducing from 3.7 to 3.5V. We only show temperature and battery levels collected during the 6 months of experimentation, due to limited space.

It is clear and interesting that the trends of the temperature and the remaining battery level are very similar. Especially, as indicated by the arrow in the figure, the minimum temperature is measured as -9°C at a.m. in 29th December, and the minimum instantaneous remaining battery level is shown at the exactly same time. This battery and temperature relationship was already known, and our long term evaluation result fits with the fact that battery levels were affected by the surrounding temperature. This result confirms that our wireless sensor network collected fine-grained sensor data successfully for 6 months.

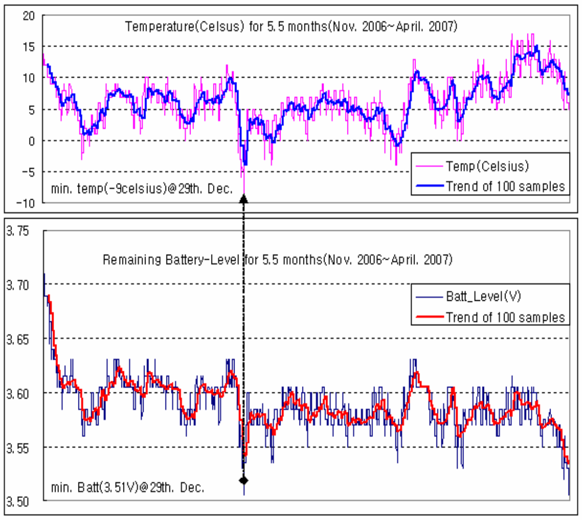


Fig. 8. Ambient temperature & remaining battery-level for 5.5 months.

5. Conclusions

In this paper, design and implementation results from our wireless sensor network experience for cultural property management has been explained. We deployed three wireless sensor networks consisting of 30 sensor nodes around a real cultural property, and ran them for 6 months. For the system, we developed a fire detection algorithm, string network topology, and periodic monitoring application, all with low power consumption and our own hardware and operating system[2]. The evaluation result from our deployment shows that our wireless sensor network has been successfully used for cultural property management.

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