Remote Health, Activity, and Asset Monitoring with Wireless Sensor Networks

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***Abstract*—Monitoring of personnel and assets in harsh or remote environments is a great challenge both from the organizational and the technical points of view. Usually, significant infrastructure investments and highly trained personnel are required. We propose a system that employs a wireless mesh sensor network to provide the communication backbone for stationary and wearable sensors. The sensor network is interfaced with a PC application through a TCP/IP connection, which allows for remote control along with data visualization and storage. The proposed system is reliable, inexpensive, rapidly deployable by minimally qualified personnel, automatically reconfigurable, and completely autonomous. It provides simultaneous monitoring of environmental and personal health and activity data and the capability of combining both for improved situation assessment. We discuss the proposed architecture and present an example system built to demonstrate the efficacy of this concept.**

I. Introduction

Recent advancements in radio technology, low power electronics, and energy generation enabled creation of vast networks of small, reliable, self-powered nodes that can create cartography of measurands over a large area. These systems, called Wireless Sensor Networks (WSNs) are composed of a multitude of wireless routers (nodes) performing attributed sensing and data processing tasks and sending the results to a destination through a wireless channel [1]. A WSN can further be used in a so-called 3-tier architecture [2] where the short range WSN (e.g. ZigBee) communicates data from sensors to a gateway, which in turn uses a wide area network (e.g. WiFi, GPRS) to relay the data to a processing and control center. In such a way, the measurands are accessible for extensive analysis and the system can be controlled remotely. WSNs find broad applications ranging from environmental through industrial monitoring to military applications [1]. In this paper, we analyze the concept of using a WSN for monitoring both personnel and assets in remote and harsh environments. We demonstrate that simultaneous monitoring of the environment along with the personal health and activity data acquisition significantly contributes to a better situation assessment by the remote system operator.

Up to now, most interest in telehealth has been geared toward remote monitoring of post operation patients and individuals with chronic diseases [3], [4]. In this paper, we address a different challenge. We propose a heterogeneous system capable of environmental monitoring, perimeter protection, localization, heath and activity monitoring and combining all this data in a distributed fashion to create context awareness. The aggregated data is used to minimize energy consumption through reduced radio communication and help avoid false alarm generation through better situation assessment. Such systems are of great interest for remote occupational health monitoring and providing safety and security to remote sites, especially in the resources and exploration industry.

II. Remote Monitoring

The concept of remote monitoring has stimulated research and development to create systems that would enable a remote operator to react in real time to abnormal situations without the necessity of physically being present at the remote site. Such idea is especially appealing in situations where the monitored site is difficult to access, or hazardous nature of its environment incites reduction of personnel physical presence. Furthermore, limiting the necessity of physical presence reduces the costs of operation. This is especially apparent in applications in the gas and mining industry, where multiple remote sites have to be secured and monitored.

Figure 1 presents a simplified architecture of a remote monitoring system. A wireless sensor network composed of routers (pegs), wearable sensor nodes (tags) and gateways is deployed in the desired location. Various sensors are connected to the pegs (environmental, security, etc.). The tag devices are either worn by employees for health and activity monitoring, or simplified versions are mounted on equipment for identification and tamper detection. Gateway devices relay the information from the WSN through a TCP/IP network to a server application maintaining an SQL database. The database is used to store all relevant data including access rights, user data, gathered data, and the alarm log. Multiple Wireless Sensor Networks (sites) can be interfaced to one server application. Finally, graphical user interface applications (GUIs) connect to the server application to retrieve information from the SQL database and control the operation of the system. The GUIs can be implemented on any platform including PCs, smartphones, or as a platform independent web application.

A. The Wireless Advantage

Wireless communication of data provides the convenience of easy installation and maintenance without concern about

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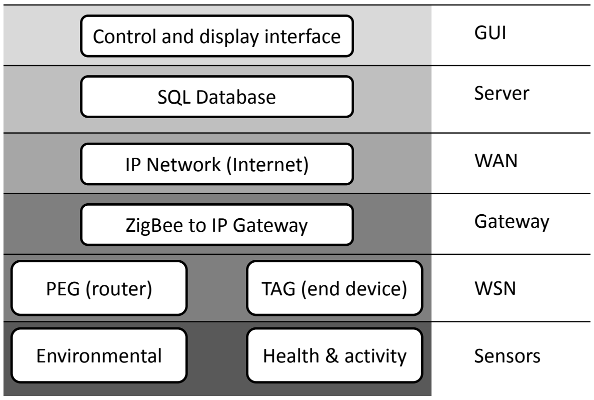

Fig. 1. Simplified architecture of the proposed remote monitoring system.

cabling and the associated quality of galvanic connections. Furthermore, if mesh architecture is used there is no fixed communication pattern. Therefore, when a node fails, its routing tasks are taken over by a healthy neighbor and the overall data communication is not affected. Furthermore, the network deployment may be planned with sufficient overhead to be able to increase the transmit power of a node whose neighbor failed in order to reach the next router. These reliability advantages make wireless mesh networks a very interesting candidate for many applications where access to devices is either difficult or expensive. Furthermore, wireless systems are much easier and faster to deploy, as the fixed infrastructure required is minimal. Thus, the proposed system can be used as a monitoring and security solution for protecting temporary operations in repair or construction sites.

B. Localization

The wireless architecture of the network enables implementation of Received Signal Strength Index (RSSI) based localization methods. Therefore, the wearable nodes (tags) can be easily localized in reference to the network of static routers (pegs). Furthermore, given that each tag device has a unique identification number, precise location of a specific person or object equipped with a tag device can be obtained in real time. Not only is it useful in emergency situations, but also allows implementing access rights to specified zones to a limited group of users.

C. Context Awareness

A very important aspect of the proposed system is its inherent context awareness [5]. The mesh architecture of the sensor network means that devices can communicate directly between each other and thus easily access information gathered by neighbors. The peg devices aggregate and pre-process the acquired data, which means that it can be effectively used to alter operation of nodes in the system, or the amount and granularity of data sent to the gateway. Depending on situation, the reporting frequency may be modified and the information gathered may be interpreted differently. For example, health and activity data will be analyzed more precisely if increased levels of dangerous gases are detected by the environmental sensors.

Another aspect of context awareness is the location of users. The interpretation of health and activity data should be affected by the specific location where those were acquired. For example, heart rate readings taken at an office should differ from readings taken from physical workers in a mine. Based on this approach, a set of rules is defined that triggers alarm generation or more precise data acquisition and transmission. Those rules can be based on the environmental readouts: temperature, gas concentration, radioactivity, intensity of electromagnetic fields, etc.; and on the health and activity data: elevated or low heart rate, stress, impacts, falls, or increased physical activity.

D. Data Security and Privacy

A very important aspect of all systems dealing with personal data is data security and privacy. The proposed system implements a three level security approach. A hardware 128 bit Advanced Encryption Standard (AES) is implemented on the device level for encryption of all inter device communications in the WSN. Furthermore, a MAC layer security is enabled requiring a pass code from every device trying to join the network. Finally, system level security requires that every device or application that tries to participate in the system must be listed as trusted in the SQL database.

III. Powering

Monitoring of people and assets in remote and harsh environments implies that the devices will be deployed in an environment where maintenance, most importantly battery replacement, is undesired either because of associated difficulty or cost. Therefore, supplying the devices with a reliable and constant energy source is crucial for successful deployments. Out of the three types of devices used in the system (gateways, pegs, and tags) only pegs are left in the field for extended periods of time. The gateways are usually deployed in the vicinity of other devices delivering the other end of the IP network and thus, given the gateway's very low power consumption, it can use the same power source with almost no detectable load increase. The tag devices are worn by employees are have to be checked in after each shift giving the possibility of battery recharge. Tag devices installed on assets often have to remain in the field for extended periods of time. Therefore, its power consumption should be carefully optimized. In our case, those devices remain asleep most of the time and are only activated upon detection of a specific event: excessive motion or an impact. In this mode, these devices can operate for over one year in the field. On the other hand, the peg devices (routers) are not only abandoned in the field, but also must remain active all the time in order to enable data communication between other members of the network. To this end, we not only carefully optimized the energy consumption of these devices, but we also equipped them with ambient energy harvesting subsystems extending their lifetime through use of solar or wind power. The ambient energy harvesting circuit is equipped with peak power tracking

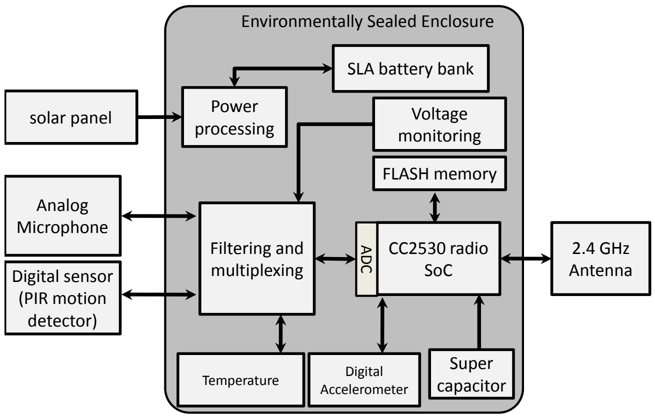

Fig. 2. Simplified architecture of the peg device.

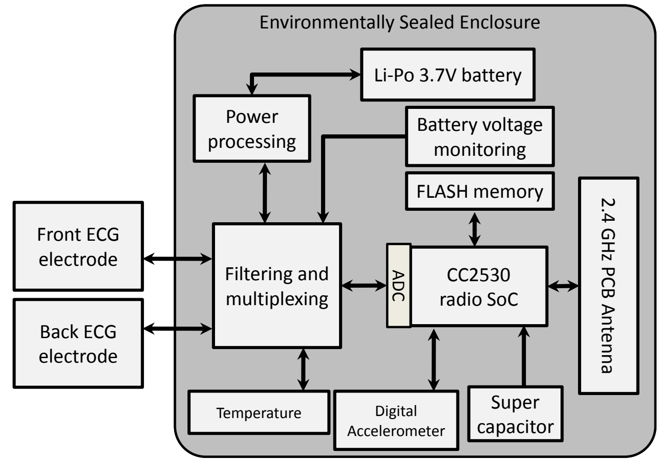

Fig. 3. Simplified architecture of the tag device capable of calculating subject heart rate along with body position and activity level.

which ensures that in all conditions, the external source is used most efficiently through adaptation of the input impedance of the circuit. This approach is universal enough to be used with various solar panels and wind generators.

IV. Example Implementation

The presented approach to remote monitoring has been used in design of a system intended to be deployed in harsh environments. It is based on the ZigBee standard [6] enabling very low power wireless communication. It is composed of wireless routers with sensors, wearable sensor nodes, ZigBee to IP gateways, a server application, and a user interface application. As presented in Fig. 1 the sensor data collected by both tags and pegs is first pre-processed on the peg devices and used for context creation and then selectively sent to the server through the gateway. The peg and gateway devices were designed to operate in extreme weather and in temperatures ranging from $-40°C$ to $+85°C$. One of the main challenges in implementing a system with such a large temperature range was to choose a proper battery type and build an adequate power processing subsystem. In this implementation, we opted for pure lead AGM SLA batteries (Enersys Cyclon) that not only meet the temperature requirements, but also have very flexible recharging characteristics.

Figures 2 and 3 present respectively the architecture of the peg and the tag device. Both are built around the Texas Instruments System-on-Chip CC2530 which is a low power ZigBee network processor. The peg devices are equipped with an energy harvesting subsystem, a universal external sensor interface, and a stack of SLA batteries. The tag device is a miniature system powered from a lithium-polymer battery. Its main purpose is to acquire and process electrocardiogram (ECG) to estimate heart rate of the subject and to acquire and process acceleration for body position and activity level. Selected peg devices were equipped with PIR motion sensors and analog microphones and all peg devices were equipped with temperature sensors and accelerometer-based tamper detection. In the current implementation, the peg devices can operate for over 4 months in constant activity when powered from a $12\,V$ $4.5\,Ah$ stack of SLA batteries only. The solar powered battery recharging circuit implemented in every peg device further extends its lifetime depending on the insolation levels. The tag device can operate for over one week when acquiring ECG and periodically communicating heart rate, body position, and activity level [7]. The tag device for asset identification and monitoring can operate for over one year when only infrequent event based activity is required.

We also implemented the IP front-end for the system. Figure 4 presents the graphical user interface (GUI) showing the convenient map-based data visualization with clickable icons for every device in the system, sensor coverage, service activation, and alarm messages.

We deployed the system in a test location at the Simon Fraser University campus in Burnaby, BC, Canada. A network composed of 9 routers and 3 tag devices was used for securing a perimeter and acquiring environmental data. Volunteers were equipped with wearable sensor nodes and asked to perform activities ranging from office tasks to fitness exercises. The system was collecting the health and activity data along with

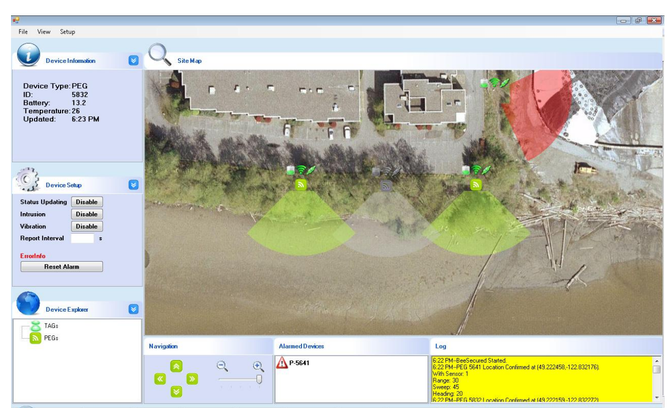

Fig. 4. Graphical User Interface used to visualize data acquired by the WSN and to provide control over services provided by the system.

subject location and the corresponding environmental data. Furthermore, we demonstrated the access right functionality by allowing only selected wearable devices in the protected zone, while holders of other tag devices or people with no devices would trigger intrusion detection alarm. The system was connected to two PCs hosting the server and GUI applications through a WiFi router Linksys WRT110.

V. Conclusion

We have presented a remote personnel and asset monitoring system employing a wireless sensor network interfaced with GUI and server applications through a TCP/IP interface. The proposed system provides environmental monitoring capabilities, perimeter protection, health and activity detection, and localization of users. It is inherently more reliable than traditional hard-wired solutions, as the system automatically reconfigures its communication pattern when a router device fails. Furthermore, such wireless system is easily expandable, modular, and adapts its operation to changing conditions. Finally, it is easy and quick to be deployed at much lower cost than comparable hard wired systems or surveillance based on human resources, as only minimal infrastructure is required. This results in less development and deployment time for each particular system, lower cost and thus shorter time to market.

We also presented an example implementation of a system based on the discussed concept. The proposed network is based on the ZigBee standard and incorporates self-powered router devices with environmental and security sensors, along with wearable nodes capable of measuring subject heart rate, body position, activity level, and location. The proposed system is an innovative, low cost, and easily deployable alternative to existing surveillance solutions.

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