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AN AUTONOMOUS NETWORKED WIRELESS DEVICE FOR STRUCTURAL HEALTH MONITORING

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Abstract

SHM is widely recognized as an important aid for improving the safety and reducing the maintenance cost of infrastructures. The expense associated with autonomous monitoring often limits this practice to structures with particular strategic, historical or economic importance. Analysis of the associated costs indicates that design, installation, software customization, and calibration comprise the bulk of the expense.

This paper describes an autonomous monitoring device designed to achieve dramatic reductions in SHM costs. The device incorporates a variety of self-referenced sensors, is battery-powered, and communicates using the GSM/GPRS mobile phone network, eliminating the need for cables. Embedded in the device are sensors for temperature, tilt, and acceleration. A digital camera, as well as displacement sensors, load cells, strain gauges, and other analog or digital sensors can be added without requiring additional conditioning electronics or power sources. The data collected, any alarms triggered, and software anomalies detected are written to the internal memory and automatically delivered through SMS messages, email, and FTP.

The cost reduction achieved by this device can potentially expand the practice of SHM to a large number of existing and new infrastructures, increasing their safety, reducing their cost of operations, and extending their useful life.

INTRODUCTION

As safety standards evolve and performance constraints become more stringent, frequent visual inspections become necessary for an increasing number of infrastructures. In the US alone, the number of bridges requiring inspection is on the order of hundreds of thousands [1]. Visual inspections are labor-intensive, costly, and highly subjective; these disadvantages are exacerbated by their limitation of detecting only visible damage, which has often reached an irreversible stage.

In contrast, SHM offers higher objectivity [2] at a considerably lower cost in the long-term [3], making it a valuable alternative to manual methods. For newer structures, SHM facilitates the transition from time-based to symptom-

based maintenance [4], which reduces costs and provides additional long-term benefits that include refinement of design guidelines. Despite these promising advantages, SHM is currently far from ubiquitous, with the initial investment required often cited as the prohibiting factor. Deployment of a conventional SHM system can cost upward of several thousand dollars [5], with installation, which includes the time-consuming task of drawing cables, comprising well over half of the total expenditure [6].

This paper describes the real-time data acquisition, communication, and alerting capabilities of the *Flood Frog*, a wireless device designed to achieve a significant reduction in SHM costs. The device incorporates a variety of self-referenced sensors, is battery-powered, and communicates using the GSM/GPRS mobile phone network, which eliminates the need for cables of any type and facilitates remote monitoring. The standard alkaline batteries included in the shock-resistant, submersible, reinforced plastic case allow for 3-4 years of continuous operation. Concurrent measurement of several environmental and structural parameters facilitates capture of an accurate snapshot of the state of the structure. Ultra-low power consumption and remote maintenance result in autonomy of the device, which enables its use in inclement weather or hostile terrain.

Recent years have witnessed the development of a number of platforms for wireless sensor networks, including MICA by Crossbow Technology® and the Intel® Mote. Our device is not intended to serve as a mote. It is an autonomous embedded system with an onboard power source, long-range communication capability, considerable computing power, data storage, embedded sensors, and an embedded signal conditioner for a wide range of structural sensors, such as load cells, or strain and displacement gauges. Furthermore, our system supplies multi-purpose software that enables the plug-and-play addition of other sensors. The simplicity of this software leads to more dependable operation than that of motes with more complex operating systems. Encapsulation of the system in a rugged waterproof and dustproof case further increases the dependability. Utilization of a general-purpose mote for structural monitoring would require considerable effort in software and hardware development, with the end-result being a more expensive, but inferior, system in terms of unattended field life, long-range communication, computing power, and sensor support.

Desirable features of the device described in this paper include ease of installation, as it typically requires only two fasteners [7]. The modular design of the system results in cost savings during the design phase, while PC-assisted configuration and one-button calibration reduce setup costs. Parameter adjustment and software upgrades can be carried out remotely, reducing the cost of maintenance and facilitating deployment in locations where real-time monitoring was previously hindered by cost or infeasibility of installation.

In its first field study, the proposed device was installed on Bridge A6531 in Osage Beach, MO, in November 2006. The objective was to detect flooding and measure water level, tilt of the structure along three axes, temperature, and battery level. The device has been communicating regularly, and the data collected is accurate, as validated by information provided by the United States Geological Service (USGS).

RELATED WORK

Most wired SHM systems feature a centralized data acquisition and communication unit, often built around a PC. This central unit provides data storage, and for online systems, long-range communication for the entire sensor network [8]. Despite suffering from well-known limitations, including sensitivity of the analog wired connections to noise, and considerable vulnerability to damage from accidents and vandalism, often biased financial considerations and the lack of practical alternatives have led to prevalence of the centralized design approach. As an example of biased economic perceptions, the practice of sensor multiplexing is widely considered to reduce equipment cost, whereas critical analysis reveals that any potential savings are offset by the cost of measures necessary for alleviating the associated problems. For multiplexed sensors with long connection cables, these problems include loss of accuracy, and increase in common mode noise, stray currents, and ground potential shifts, all of which necessitate costly add-on solutions such as electrically-insulated analog amplifiers.

In the past decade, several research efforts [9-20] have focused on the development of wireless networked devices for SHM. The majority of these systems appear to be purpose-built for the collection of dynamic vibration data; a choice that has implications in both hardware and software. The rapid changes in this data necessitate fast analog-to-

digital converters (ADCs), large static memory, and significant processing power for the hardware. The corresponding software includes a complex operating system that provides sophisticated networking services such as distributed cooperative computation and sampling time synchronization [13]. Systems built on existing wireless sensor platforms such as Crossbow® motes [13, 17, 18] are constrained by the limitations (e.g., limited onboard data storage, software complexity, lack of long-range communication capability) of these motes, which are general-purpose sensing platforms and have not been designed with consideration of the unique requirements of SHM. Furthermore, with few exceptions (e.g., [19]) all of these wireless platforms exhibit the centralized design approach typical of wired systems, relying on a laptop for data processing and connection to the Internet, which severely limits their autonomy and unattended field life.

DESIGN OBJECTIVES

Recent literature, including the aforementioned studies [9-20], highlights the advantages of wireless SHM, in particular as related to reductions in installation time and cost, but few of the proposed systems appear to be commercially available as field-ready devices. In the few studies where sensors other than accelerometers are incorporated into the system, the ADC resolution is often inadequate, and the end user is burdened with at least part of the necessary signal conditioning. Moreover, with few exceptions, the end user is also required to develop ad-hoc software based on a complex embedded operating system, and is also responsible for addition of the hardware and software needed for long-range communication. As a result, the end user incurs considerable costs associated with design, development, and customization of the wireless SHM system. These costs are difficult to estimate and can easily offset the potential savings in time and cost offered by the choice of a wireless system over its wired equivalent.

Field experience, as well as analysis of existing wired SHM systems, led to the following objectives for the design and development of the wireless SHM device described in this paper.

- *Reduction of customization costs* through pre-installed multi-purpose software.
- *Reduction of installation and configuration costs* through the inclusion of an embedded power source and long-range multi-band modem, plug-and-play sensor support, and self-calibration.
- *Flexibility* through the incorporation of several embedded sensors, as well as signal conditioners for a variety of additional SHM sensors, and high-resolution auto-zeroing data acquisition channels with excitation capability for passive sensors, and local data storage and processing.
- *Reliability* through rugged packaging, fault-tolerant power source design, tamper sensors, jamming detection, long-range communication through the standard cell phone infrastructure, one or more hardware watchdogs, software error traps, and hardware self-test features.
- *Reduction of maintenance costs* through the use of long-lasting batteries in conjunction with ultra-low power design, “heartbeat” communication windows, and remote software upgrade and configuration capability.

DEVICE DESCRIPTION

The SHM device proposed to fulfill the objectives of the previous section is a wireless embedded system, termed the *Flood Frog*. The ultra-low power design of the system enables several years of operation with a standard battery pack. The data is acquired using embedded sensors, then aggregated, processed, and reported by the device in real time. In batch production, the device can be manufactured for less than $300 per unit, which is orders of magnitude less than existing SHM solutions, the majority of which have to be embedded in a structure at the time of construction. The wireless nature of the system makes it more robust, and eliminates the considerable cost of drawing cables to the site.

The device has been designed to overcome the limitations of current monitoring systems, including high cost, high power consumption, extensive use of cabling and lack of real-time data acquisition and communication capabilities. The low cost of the device facilitates installation in areas where monitoring has been rendered infeasible due to the associated cost. Ultra-low power consumption enables the use of batteries instead of traditional power lines, while reducing the cost of installation and allowing deployment in locations that are off the power grid. Wireless communication through an existing infrastructure such as the GSM cellular network greatly increases flexibility and

ease of installation. To avoid frequent battery replacements and allow several years of unattended field life, the device utilizes hardware and software mechanisms for reducing power consumption. These techniques include event-driven execution, code optimization, switching off hardware peripherals when not in use, and varying the clock frequency used based on the circumstances.

For bridge SHM applications, including flood monitoring, the device will be installed near a riverbed or on a bridge girder, where submersion and high humidity are likely; hence, a water tight enclosure is necessary and has been provided. The case chosen for the first prototype is 7.5 x 5 x 4 inches, conforms to the IP 68 standard, and protects against the effects of constant submersion in water. The case design is depicted in Fig. 1. The small size of the device facilitates its installation in unattended locations, where a conspicuous device would be subject to vandalism. Any perforation in the box will increase the risk of leakage, so the box is completely sealed, with the exception of a small perforation for the water level probe. The entire system is enclosed in the case and operates wirelessly. The flood sensor is implemented as a floater inside a hollow vertical pipe affixed to the pier; the position of the floater indicates the water level. In order to communicate this information to the device, a magnet is embedded inside the floater and two magnetic switches, depicted in blue and red in Fig. 1, are installed inside the case. A third magnetic switch, depicted in yellow in Fig. 1, is provided as an anti-tampering mechanism.

Fig. 2 illustrates the hardware architecture of the Flood Frog. The power supply, located in the upper left corner of the figure, powers the entire device, and is connected to every component. For clarity, the wires connecting the power supply have not been depicted in the figure. The core of the device is comprised of two main components, the microcontroller unit (MCU) and the GSM module. They are connected through a serial interface, which can also be used to communicate with a PC for programming and debugging purposes. The RS232 block is a level translator necessary for communication between the PC serial port (DB-9 connector) and the MCU/GSM serial port.

The GSM module is a quad-band mobile modem/phone and supports voice calls by utilizing the microphone and speaker. The module can also take pictures with the embedded camera, and transmit them through multimedia messages or via GPRS. The MCU and the GSM module are connected by a Serial Peripheral Interface bus (SPI), which is a channel that allows bus-based serial communication. The bus also connects to external memory for data storage, and to a wireless socket that can connect the SHM device to a local wireless sensor network for which it serves as a base station.

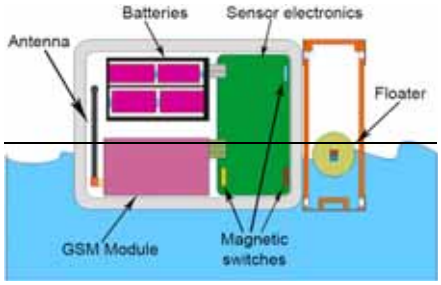

Figure 1. Case design of the proposed SHM device.

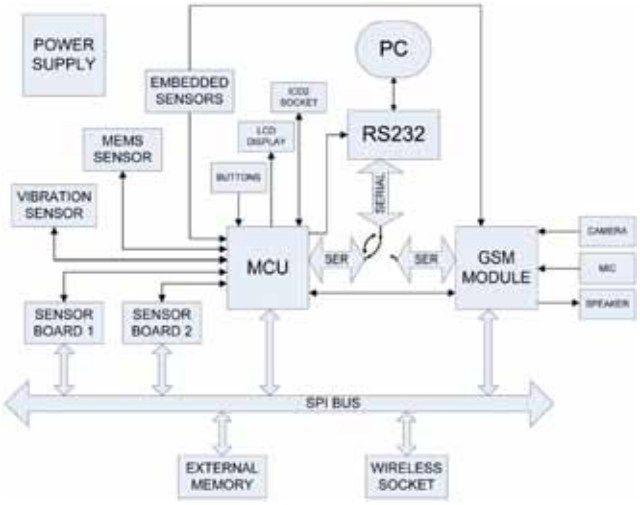

Figure 2. Hardware architecture of the proposed SHM device.

The embedded sensors, which measure water level, temperature, acceleration, tilt, and vibration are directly mounted onto the main board and trigger alarms in case of flooding and/or enclosure tampering. The switches are connected to both the MCU and the GSM module. The MCU also monitors the battery level. Three additional sensor blocks have been provided; two of them are general purpose (boards 1 and 2), and intended to allow the addition of sensors such as load cells, strain gauges and motion potentiometers. The third is specifically designed for earthquake monitoring, i.e., vibration detection. The two general purpose boards are linked to the SPI bus to allow direct communication with all other connected peripherals. The Micro Electro-Mechanical Systems (MEMS) sensor block embeds a 3-axis accelerometer that can be used to sense and measure motion and tilt. The internal ADC of the MCU digitizes the analog signals transmitted by all three sensor boards.

To expand the data storage capacity of the Flood Frog, external flash memory has been installed onboard. The limited 256 Kbit size of this flash memory is considerably smaller than that of the GSM module, but this choice leads to significantly less power consumption, and is appropriate for applications that generate limited data.

REAL-TIME COMMUNICATION AND MAINTENANCE COSTS

In many SHM applications, timely communication of the collected data is of paramount concern. As described in the previous section, the proposed SHM device is equipped with a worldwide-compatible quad-band GSM module, which allows GPRS data transfer of 8-24 Kbps upstream and 24-48 Kbps downstream, and provides SMTP and FTP capabilities, in addition to email. The GSM module is the main source of power consumption in the SHM device; therefore it is normally kept off. In order to communicate, the GSM module needs to be switched on and enrolled in the network. Timing of the GSM transmission is affected by network conditions such as signal strength, electromagnetic noise and traffic volume in the mobile cell and the entire network. To increase the reliability of communication, any alerts generated are sent by SMS to more than one recipient. For email, redundant SMTP servers are used to diminish the probability of delayed deliveries. FTP communication does not have this problem, as once the connection is established the file is delivered directly to the final server. This advantage can be leveraged by developing a PC application that constantly checks for the presence of new files.

Assuming no unusual delays in communication, delivery of an alarm composed of SMS, email, and FTP takes a total time of 50 seconds from when the device exits sleep mode [21]. This is a very good result, mainly because the first alarm, sent by SMS, is most likely received after 20 seconds, and the second alarm, which is sent by email, after 30 seconds. Considering that even for severe flash floods the water takes several minutes to reach a dangerous level, the proposed device is considered to be satisfying real-time constraints. The aforementioned delay values were measured on the prototype, and reflect worst-case estimates.

Wireless communication is one of the main advantages of the proposed SHM device. Eliminating the need for wires significantly reduces the installation cost and facilitates the use of a sealed enclosure for the device. Acquiring a local SIM card allows for an SMS to be sent or a GPRS connection to be established to the Internet for only a few cents. The charges are usually based on the actual traffic exchanged, and the fixed fees are negligible. Assuming that the heartbeat signal and reporting of the device take place via a daily SMS and two weekly data transfers through all communication channels (SMS, email, and FTP), the annual cost of communication is less than $80. This figure assumes 5KB emails and 30 KB FTP transactions, both of which are generous estimates. When necessary, firmware updates and configuration changes are pushed onto the device during the daily heartbeat connection. In light of the long battery life, these updates are the only maintenance required; hence, the annual maintenance cost is included in the $80 annual cost of communication.

FIELD TEST

The first prototype of the system was deployed on Bridge A6531 in Osage Beach, MO in November 2006. Fig. 3 depicts the installation. In this figure, the device is circled and the cable affixed to the pier is the probe used to measure the water level. Since being installed, the device has delivered a daily heartbeat message through SMS and email and has uploaded the acquired data to the FTP server. Figure 4 depicts the reported data. The water level measurements have been validated with values published by the USGS, and are accurate within 10%, which is an acceptable result given the margin of error of the USGS values.

Figure 3. Installation on Bridge A6531 in Osage Beach, MO.

CONCLUSIONS

Real-time monitoring of structures increases safety and reduces costs by guiding maintenance efforts and generating early warning of potentially disastrous events. This paper describes an autonomous device for real-time environmental and structural monitoring. The device incorporates embedded sensors and allows for the connection of additional analog or digital sensors. Water level, temperature, tilt, and other collected data are reported by SMS, email, and FTP, along with any alerts generated as a result of anomalies in the data or device performance. Battery power, in conjunction with use of the GSM cellular network for data communication and remote maintenance result in a completely wireless device capable of several years of unattended field life. Deployment of the first prototype on a bridge in Missouri has validated real-time data acquisition and communication. Ease of installation and maintenance, as well as the significant reduction of their respective costs, facilitates the broad deployment of this SHM device.

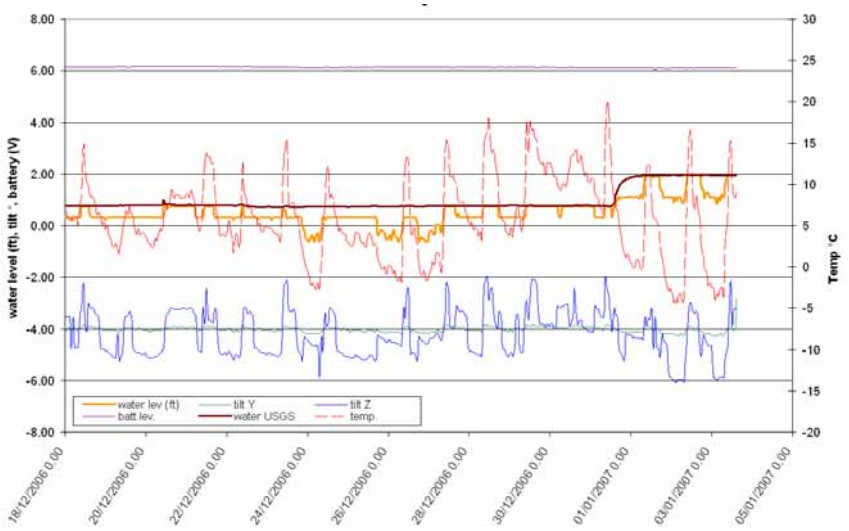

Figure 4. Sample report of temperature, water level, and pier tilt data.

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