A Wireless System for Real-Time Environmental and Structural Monitoring ⋆

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Abstract. Accurate real-time monitoring of structural health can result in significant safety improvements, while providing data that can be used to improve design and construction practices. For bridges, monitoring of water level, tilt, displacement, strain, and vibration can provide snapshots of the state of the structure. Real-time measurement and communication of this information can be invaluable in guiding decisions regarding the safety and remaining fatigue life of a bridge. This paper describes the real-time data acquisition, communication, and alerting capabilities of the Flood Frog, an autonomous wireless system for remote monitoring. Battery power and utilization of the GSM cellular network result in a completely wireless system. Coupled with the low cost of the device, the elimination of cables allows deployment in locations where autonomous monitoring is hindered by cost or infeasibility of installation. The first prototype of the system was deployed in Osage Beach, MO in November 2006.

1 Introduction

Early warning and advanced preparation for emergency are two of the most effective lines of defense against natural disasters such as floods, earthquakes, and hurricanes. The impact of catastrophic events, including the recent hurricanes Katrina and Rita, underscores the limits of established early warning systems, especially with regard to rapidly evolving situations. Environmental monitoring, which refers to measuring and recording parameters such as temperature, humidity, salinity, water level, acoustic emission and pollution for a selected site, enables early detection of potentially disastrous events. Timely provision of information facilitates recovery efforts and aids in the containment of aftereffects.

Structural monitoring is another important issue, as periodic collection of information about the health of a structure, such as a bridge or a building, can prevent sudden breakdown, save money, and most importantly, protect human lives. In this context, changes in tilt, displacement, strain and vibration can serve as warnings for impending structural damage or even collapse. Regardless of the phenomenon being monitored, the information should be collected and communicated with resolution and frequency sufficient to enable accurate and timely knowledge of the situation.

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In monitoring applications, one major challenge is the infeasibility of installing the necessary devices in remote areas or hostile environments. As an example, low water bridges, which are prone to flooding, are typically located in rural areas that lack accessible power and communication lines. The problem is further exacerbated by the costs associated with digging trenches and drawing the wires needed for a wired system. Physical installation challenges have been addressed in our previous work [1].

The aforementioned challenges underscore the necessity of a novel monitoring system that is less costly, more dependable, and more flexible in terms of locations where it can be installed. Furthermore, for a broad range of environmental and structural phenomena, there is a critical need for autonomous real-time acquisition and communication of data.

The solution proposed in this paper 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 batch production, the device can be manufactured for less than $300 per unit, which is orders of magnitude less than existing 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 savings achieved in installation and maintenance costs facilitate large scale deployment of the system.

The design of the Flood Frog is general, and includes an onboard digital signal processing unit with an embedded A/D converter (ADC), which allows the use of digital or analog sensors. Communication is completely wireless and uses the existing GSM cellular infrastructure. Despite being battery-powered, the device acquires and communicates data in real time. The first prototype of the system was deployed in Osage Beach, MO in November 2006, and has been communicating accurately since, as validated by data provided by the United States Geological Service (USGS).

Recent years have witnessed the development of a number of platforms for wireless sensor networks (WSNs), including motes manufactured by Intel and Crossbow. 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 that can support a wide range of additional 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 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 system that is inferior in terms of unattended field life, long-range communication, computing power, and sensor support.

The remainder of this paper is organized as follows. Section 2 presents relevant research in real-time monitoring systems. Sections 3 and 4 describe the hardware and software of the system, respectively. The prototype and field test are discussed in Section 5. Section 6 concludes the paper.

2 Related Work

Accurate monitoring of structures and their surrounding environment is an area of critical need, and the development of embedded systems for this purpose has been of interest to the research community. This section presents several relevant studies.

In FloodNet [2], wireless sensor nodes deployed in a river bed are used to collect data that is later used for flood prediction. The system does not operate in real time, as the main purpose is collection of data to be fed to a simulator. A related system, described in [3], also uses a WSN to collect data for flood prediction, but carries out the computation locally, using a grid-based approach.

A study performed by the Meteorological Development Laboratory of the US National Weather Service is described in [4]. The approach taken involves the processing of current radar information and monitoring of precipitation to predict flood. Other studies, presented in [5] and [6], use satellite and microwave images to monitor floods. The main disadvantage of such approaches is the prohibitively high cost of acquiring radar and satellite data. Moreover, the predictions are not made in real time, and are subject to human error.

Another flood monitoring device is described in [7], which describes a flash flood alerting system that uses a WSN to track a flood as it evolves. This system is still in the conceptual design phase, and as of the date of this publication, a prototype does not appear to be under development. Two predictive flood monitoring systems are presented in [8] and [9]. In both studies, measurement of the extent and distribution of flooding during severe weather conditions is utilized to generate maps for future analysis and prediction. IN4MA [10] manufactures commercial systems for monitoring rainfall and river levels in order to minimize the damage caused by flooding. The data collected is communicated over the GSM network. In contrast to the Flood Frog, which has been designed to be easily expanded by wireless nodes to create a local WSN, the IN4MA device can only operate as a standalone unit. Campbell Scientific [11] is another company that develops monitoring systems for flood and other environmental phenomena. They offer precipitation, wind speed, soil moisture and water quality measurement through a set of modular devices. The cost of a complete system is orders of magnitude higher than that of our proposed system.

A wireless environmental monitoring system is presented in [12]. It describes the design and implementation of a reactive and event-driven network for monitoring soil moisture. The study presents data about the field life of the device; the maximum duration is approximately one month, whereas the Flood Frog can operate for several years on a standard battery pack. A similar system is presented in [13]. This study introduces the "Sensor Web," which is a platform that combines in situ and remote sensing to collect information about the environment. One significant difference between this project and our work is their use of satellites as a means of long-range communication, which is very costly and incapable of frequent updates. Low power consumption has not been addressed for the system, which again constrains unattended operation.

The study in [14] presents a wireless strain sensing system for structural health monitoring. This system shares a number of features with the Flood Frog, but is limited to strain sensing and does not allow for the addition of other sensors. Another structural monitoring system is presented in [15], where a wireless base station and several sensor nodes are deployed in a building. The system is not capable of long-range communication and requires periodic inspections for data collection. An improvement to this system is presented in [16]. The communication range of this system is still limited, as it cannot utilize the cellular phone system, and the field life of less than one year is considerably shorter than that of our system.

An important difference between the work proposed in this paper and other existing systems is that the Flood Frog has been designed as a general-purpose monitoring system that can be customized for various applications. Data acquisition, communication and alarm generation occur in real time for all monitored phenomena. Considering the high power consumption typically associated with real-time operation, the ultra-low power consumption of the system is a significant achievement.

The studies mentioned above demonstrate the wide range of applications that can benefit from a device such as the Flood Frog. Each application presents different requirements, from site monitoring to collection of data for forecasting.

3 Hardware Implementation and Features

In the context of this paper, *monitoring* refers to continuous evaluation of the quantities under consideration. If the data is acquired, and any necessary alarms are generated within acceptable time limits, *real-time monitoring* has been accomplished. The specific time limits imposed depend on the monitored phenomena, and can range from seconds to hours, based on the urgency of subsequent countermeasures. For example, closing a bridge in case of flooding should happen within an hour, while the inspection needed to investigate excessive strain on the bridge can occur within several days without compromising the safety of the structure.

The structural and environmental phenomena monitored by the Flood Frog generally evolve slowly. Quantities such as temperature, humidity, water level, tilt, displacement, and strain vary slowly; therefore, a sampling period on the order of seconds or minutes will suffice.

Flash flooding is an example of a critical situation well-suited to the monitoring and alerting capabilities of the Flood Frog. According to the National Oceanic and Atmospheric Administration [17], flash floods can occur within a few minutes of excessive rainfall, dam or levee failure, or sudden release of water held by an ice jam. For such phenomena, a sensor sampling period of minutes can easily provide for real-time monitoring, with prompt alarm generation whenever a threshold is exceeded.

In contrast, the monitoring of vibration makes real-time operation more challenging, as it is a rapidly-evolving event. The Flood Frog incorporates additional hardware to enable timely acquisition of such data. Signal conditioning is carried out to reduce the amount of data communicated over the GSM network, resulting in a significant decrease in power consumption.

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 Flood Frog 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 Flood Frog 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.

The device includes onboard sensors for water level, temperature, acceleration, tilt, and vibration. Flood detection is carried out by a magnetic switch used to sense the position of a magnetic floater in the water. The actual level of the water is measured by a capacitive sensor. Acceleration and tilt are sensed with a MEMS three-axis accelerometer that supplies three analog signals, one for each direction. Lastly, vibrations are captured by a piezoelectric sensor. Excluding the magnetic sensor, which is a simple on/off switch, all other sensors are analog, and therefore their output needs to be digitized. This is accomplished by the internal ADC of the onboard microcontroller unit (MCU). Several additional analog channels have been included to allow the addition of sensors such as load cells, strain gauges and motion potentiometers.

4 Software Implementation and Features

The Flood Frog is an embedded device built from the ground up, and its unique requirements necessitated the development of a custom real-time operating system (RTOS). We chose not to use an off-the-shelf RTOS to keep the software as simple as possible, implementing only necessary features. The main requirements for the software are real-time functionality, compact code, reliability, efficiency, and power-awareness. In developing the software, the main objective was to create the smallest and least complex OS capable of carrying out all required operations within specified time constraints.

The software design takes into account the limited energy available to the device by reducing computation and keeping the device in sleep mode for as long as possible. This can be achieved by writing efficient code and by manipulating the hardware capabilities, e.g., placing the peripherals in "off" state when they are not in use. Disabling the peripherals poses a significant challenge in view of the real-time capabilities of the Flood Frog, as the device may not be able to access available resources immediately. The challenge is to find the best tradeoff between power consumption and the monitoring duty cycle, while meeting timing constraints.

The powerful onboard computational unit eliminates the need for multitasking. The MCU has a 16-bit 30-MIPS processor, which is more powerful than an Intel 80486 (20-MIPS) chip. Sequential operation results in greater dependability, due to the relative ease of troubleshooting a single flow of execution. The only task that may require a fast real-time reaction is the vibration alarm; in that case, the device is switched on as quickly as possible in order to avoid loss of information.

The Flood Frog can be used in either time-driven or event-driven fashion. As a time-driven device, the data collected by the sensors is recorded periodically, and the device remains in sleep mode unless it is recording data or an exception occurs. The recorded data is compared with preset thresholds, and alarms are triggered as necessary. In event-driven mode, the device wakes up in response to specified events, the occurrence of which is detected by the sensors. An interrupt is configured for each event, and causes a wake up of the device and the activation of its interrupt service routine (ISR). The current prototype of the system provides ISRs for timer, flood, and vibration interrupts.

Vibrations occur suddenly, and can happen during the long sleep periods when data cannot be recorded. To overcome this problem, once vibration is detected, the analog signal is immediately sent into an analog delay line that provides enough lag to allow the sampling circuit to be switched on. Meanwhile, the MCU senses the vibration interrupt and invokes the appropriate ISR, which immediately wakes up the Flood Frog. In case the oscillation exceeds the specified threshold (e.g., during an earthquake), an alarm is triggered. This technique allows real-time monitoring of sudden phenomena such as vibration with limited battery power.

To maintain autonomy, the device must retain minimal functionality even when in sleep mode. As a result, the software must run continuously, but the system should be kept in low-power mode whenever possible. In the event of an exception (e.g., math, stack, or oscillator errors) or other failure, a complete hardware and software reset (i.e., reboot) of the device may be necessary for returning it to a safe and predictable state.

Figure 1 depicts the software state diagram of the device. The software execution flow has a single entry point, where the software begins initial operation and to which the software returns in the event of system reset. The source of each system reset is determined immediately and flagged in an internal register.

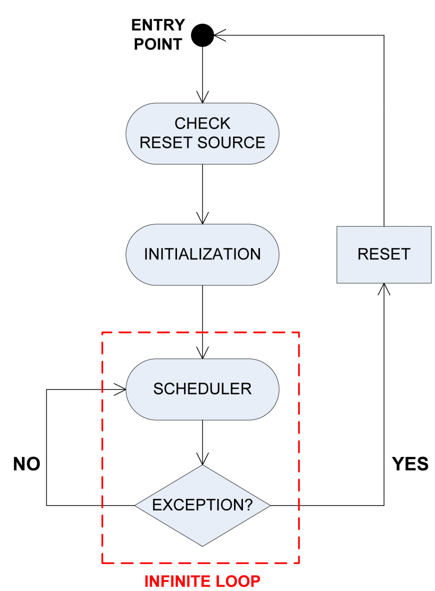

Fig. 1. Software state diagram.

At the entry point to the software, after the reset source is determined, an initialization routine is performed to prepare the various hardware components for operation. A complete execution cycle of the infinite loop is comprised of two phases: the sleep period and the scheduler check.

The first task of the infinite loop is to place the device in sleep mode. When its sleep timer expires (i.e., every 1 second) the device wakes up and updates the internal clock and counters. Other interrupts (e.g., flood, vibration) may also wake up the system and demand immediate service.

The task queue is implemented as an array where ready processes are placed, ordered by priority, with the highest priority being assigned to vibration, as it requires a rapid response. If the scheduler stack is not empty, the first task is popped and executed; when it is completed, the next task, if any, is popped. If the queue is empty, the device is returned to sleep mode. This design results in a very simple and computationally efficient execution flow.

In real-time monitoring, it is important to communicate the data in a timely manner. As explained in Section 1, we utilize the existing GSM network infrastructure to increase flexibility and ease of installation, while meeting delay constraints. The Flood Frog 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 Flood Frog, therefore it is normally kept off. The communication time is dictated by the GSM network.

In order to communicate, the GSM module needs to be switched on and enrolled in the network. These two steps require about 15 seconds. After enrollment, an SMS can be sent in 5 seconds, a 512-character email in 10 seconds, and a 5000-character text file, through FTP, in 20 seconds. The limitation on email length is due to the particular GSM module used. There is no limit on the amount of data exchanged by FTP. A text file of 5000 characters suffices for most situations, as numerical sensor data is compact. In case a 10000-character file is needed, the total transmission time becomes 27 seconds.

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. If the signal is weak, enrollment can be delayed or interrupted, while external electromagnetic noise can temporarily disrupt the communication. Traffic is also an issue, as a congested cell can prevent the device from communicating. Successful transmission of an SMS by the GSM module implies delivery to the message server, and not to the final recipient; this message server can sporadically be backlogged, delaying delivery to the final recipient. Similarly, email communication is through an SMTP server, which can delay delivery during high-traffic periods. The delay values discussed above were measured on the prototype, and reflect worst-case estimates.

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. The 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. 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 [17], our device is satisfying real-time constraints.

A large amount of data can be sent by FTP in a relatively short period of time. Once an alarm is received by SMS and/or email, the data uploaded to the FTP server can provide a complete picture of parameter trends in the period before the alarm, allowing analysis of the situation. Implementing the aforementioned PC application would provide an additional means of triggering alarms in real time.

5 Prototype and Field Test

In its first field study, the Flood Frog was installed on Bridge A6531 in Osage Beach, MO in November 2006. The objective was to detect flooding and measure water level, temperature, battery level, and tilt of the structure along three axes. The case chosen for the prototype is 7.5x5x4 inches and 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 magnetic switches are installed inside the case.

The case design is depicted in Fig. 2. Figure 3 shows the device, circled in red, affixed to the pier. The yellow cable is the probe used to measure the water level. Since being installed, the Flood Frog has delivered a daily heartbeat message through SMS and email and has uploaded the acquired data to the FTP server. The water level data has been validated with values published by the USGS, and is accurate within 10%, which is an acceptable result given the margin of error of the USGS values.

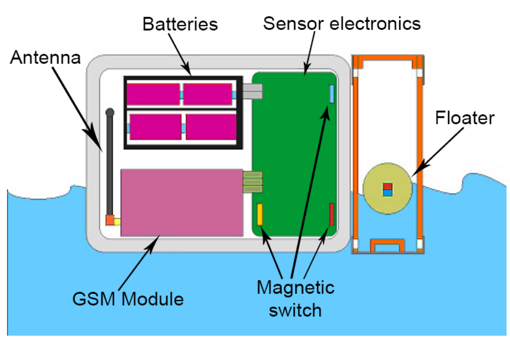

Fig. 2. Block diagram of the Flood Frog.

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

6 Conclusions

This paper describes an autonomous real-time device for environmental and structural monitoring. The device incorporates embedded sensors, is battery-powered and communicates using the GSM/GPRS cellular phone network, eliminating the need for cables of any type. The data collected, any alarms triggered, and software anomalies are automatically reported to designated recipients through SMS messages, email, and FTP file upload. The specific application discussed is flood monitoring, for which the device meets real-time constraints on data acquisition and communication.

The cost reduction achieved by the Flood Frog has the potential to expand the practice of structural health monitoring to a significantly higher number of existing and new structures. This improvement will increase safety and reduce the cost of operations by facilitating real-time monitoring, which in turn yields a more efficient maintenance schedule. Additionally, the general design of the device facilitates adaptation to alternative applications. Its low cost and ease of installation enable deployment in a broad range of locations, facilitating early warning of catastrophic events and potentially reducing casualties.

References

1. V. Plessi and F. Bastianini and S. Sedigh-Ali: An autonomous and adaptable wireless device for flood monitoring. In: Proc. 30th Annual IEEE Int'l. Computer Software and Applications Conference (COMPSAC06). Volume 2. (2006) 378–379
2. D. De Roure: Improving flood warning times using pervasive and grid computing. http://envisense.org/floodnet/ingenia/ingenia.htm
3. D. Hughes et al.: GridStix: Supporting flood prediction using embedded hardware and next generation grid middleware. In: Proc. IEEE Int'l Symp. World of Wireless, Mobile and Multimedia Networks (WoWMoM). (June 2006)

4. NOAA - National Weather Service: Flash flood monitoring and prediction (FFMP). http://www.nws.noaa.gov/mdl/ffmp/index.htm (Mar. 2006)
5. J. F. Galantowicz: High-resolution flood mapping from low-resolution passive microwave data. In: Proc. IEEE Intl. Geoscience and Remote Sensing Symposium (IGARSS 02). Volume 3. (2002) 1499–1502
6. M. Temimi et al.: Near real time flood monitoring over the Mackenzie River basin using passive microwave data. In: Proc. IEEE Intl. Geoscience and Remote Sensing Symposium (IGARSS 04). Volume 3. (2004) 1862–1865
7. M. Castillo-Effen: Wireless sensor networks for flash-flood alerting. In: Proc. 5th IEEE Int'l. Caracas Conference on Devices, Circuits and Systems, Dominican Republic. (2004) 142– 146
8. S. Dellepiane et al.: SAR images and interferometric coherence for flood monitoring. In: Proc. IEEE Int'l. Geoscience and Remote Sensing Symposium (IGARSS '00). (July 2000) 2608–2610
9. Y. Shao et al.: Chinese SAR for Yangtze River flood monitoring in 1998. In: Proc. IEEE Int'l. Geoscience and Remote Sensing Symposium (IGARSS 00). (July 2000) 2495–2497
10. IN4MA Remote Monitoring Solutions: Wireless outstations for flood warnings. http://www.in4ma.co.uk
11. Campbell Scientific, Inc.: ALERT flood warning. http://www.campbellsci.com/flood-warning (2001)
12. R. Cardell-Oliver et al.: A reactive soil moisture sensor network: design and field evaluation. In: Int'l J. Distributed Sensor Networks. (2005) 149–162
13. K. A. Delin et al.: Sensor Web for spatio-temporal monitoring of a hydrological environment. In: Proc. 35th Lunar and Planetary Science Conf. (2004)
14. S. W. Arms and C. P. Townsend: Wireless strain measurement systems - applications and solutions. (Oct 2003)
15. J. P. Lynch et al.: Advanced wireless structural monitoring: Past, present and future. The John A. Blume Earthquake Engineering Center, Issue 28 (2001)
16. Y. Wang and J. P. Lynch and Kincho H. Law: A wireless structural health monitoring system with multithreaded sensing devices: Design and validation. Structure and Infrastructure Engineering - Maintenance, Management and Life-Cycle Design & Performance **3**(2) (2007) 103–120
17. National Oceanic and Atmospheric Administration (NOAA) and National Weather Service (NWS): Flash floods: a preparedness guide. http://www.nws.noaa.gov/om/brochures/ffbro.htm (1992)