Wireless sensors for wildfire monitoring

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ABSTRACT

We describe the design of a system for wildfire monitoring incorporating wireless sensors, and report results from field testing during prescribed test burns near San Francisco, California. The system is composed of environmental sensors collecting temperature, relative humidity and barometric pressure with an on-board GPS unit attached to a wireless, networked mote. The motes communicate with a base station, which communicates the collected data to software running on a database server. The data can be accessed using a browser-based web application or any other application capable of communicating with the database server. Performance of the monitoring system during two prescribed burns at Pinole Point Regional Park (Contra Costa County, California, near San Francisco) is promising. Sensors within the burn zone recorded the passage of the flame front before being scorched, with temperature increasing, and barometric pressure and humidity decreasing as the flame front advanced. Temperature gradients up to 5 C per second were recorded. The data also show that the temperature slightly decreases and the relative humidity slightly increases from ambient values immediately preceding the flame front, indicating that locally significant weather conditions develop even during relatively cool, slow moving grass fires. The maximum temperature recorded was 95° C, the minimum relative humidity 9%, and barometric pressure dropped by as much as 25 mbar.

Keywords: Wireless sensor networks, wildfires, TinyOS, motes

1. INTRODUCTION

Wildfires are increasingly expensive disasters in terms of both property damage and life safety. Wildfires often occur in environmentally sensitive regions such as national parks, wilderness areas, or along the growing, environmentally and economically sensitive urban-wildland interface. Environmental monitoring in such terrains must be environmentally appropriate, which requires easy to install, low maintenance, non-toxic and preferably inexpensive instrumentation. One way to monitor wildfires and impending wildfire conditions is by using wireless, low-power sensor technology to collect environmental data such as temperature, relative humidity and barometric pressure, along with a GPS-determined location for the collected data.

Wildfire monitoring systems may be pre-deployed in wildfire prone terrains, or deployed as an *ephemeral* GPS and environmental wireless sensor network, designed to be rapidly deployed in destructive, environmentally hostile environments such as evolving wildfires. The project described in this paper was conceived as a component of a broader, interdisciplinary effort funded by the US National Science Foundation Information Technology Research program for developing a set of real-time database management and wireless data acquisition tools for rapid and adaptive assessment of the impact of catastrophic events such as earthquakes, fires, hurricanes, or floods.

The specific goals of the project include: developing and field testing proof-of-concept wireless sensor technology for wildfire instrumentation; developing and field testing an asset tracking system for location and environmental monitoring of firefighting personnel; and, investigating possible "spin-off" applications in other domains, such as monitoring of structural health, geologic hazards and or environment. In addition, successful field testing provides data that may be useful for advancing fire science, for helping firefighters, and for designing future generations of sensors and sensor platforms as limitations in the currently deployed technology are identified.

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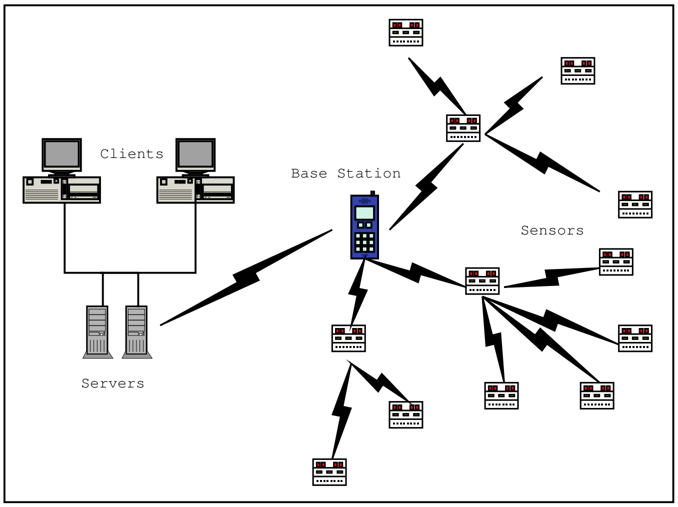


Figure 1. Wireless sensor wildfire monitoring system architecture.

2. THE WILDFIRE MONITORING SYSTEM

The wildfire monitoring system is designed to be platform independent, simple to deploy and use under extreme stress conditions, and to require minimal training for operating the system after deployment. A schematic architecture of the system is shown in Fig. 1. The collected data from motes is stored into a MySQL database, which is queried by a browser-based client interacting with a web server database bridge. The architecture allows the system to be operated using any web browser. The web application is written as a set of user friendly web pages abstracting the mechanics of the database operation away from the user. Standard, off-the-shelf technology was used for each part of the system, including commercially available motes, web server and database server. Each element of the system interacts with others through well-defined interfaces, which greatly eased the implementation.

2.1. Motes

The sensor motes are composed of the mote platform with an independently mounted sensor board. This separation allows hardware and software development of the wireless sensing network to proceed independently as well. The sensors are aggregated on a printed circuit board which plugs into the Mica2 mote. The Mica2 mote, manufactured by Crossbow Technology, Inc., hosts an Atmel 128L CPU running the Tiny Operating System (TinyOS), executing programs written in the nesC (1) programming language. Since the Mica2 mote platform is commercially available from Crossbow, Inc., hardware design for the motes only required specifying the sensors for the sensor board, which connects to the Mica2 using a 52 pin connector. The Mica2 platform operates a Chipcon1000 radio on 433 MHz frequency. The mote is controlled by an Atmel 128L 8 bit microprocessor, and has an 32 kHz external clock and RAM available.

The Crossbow, Inc. MTS420CA "Fireboard" is a separate component from the Mica2 mote and connects to the mote using a 52 pin connector. The Fireboard has two ADG715 switches mounted in parallel on an I2C bus. Switch 0 controls the power to the sensors; switch 1 controls I/O functionality. The switches may be operated independently of each other, allowing the application to control the power to each sensor to reduce power consumption. The Fireboard is also equipped with a 256 byte EEPROM. The architecture of the Fireboard is derived from the Mica Weatherboard used for the Great Duck Island study (2), and hosts barometric pressure sensor, temperature, relative humidity, acceleration, light intensity and LeadTek 9546 GPS location sensors. For the field testing described later in the paper, the light and acceleration sensors were not used.

The LeadTek 9546 GPS unit has 12 channels "All-In-View" satellite tracking with cold/warm/hot start times of 45/38/8 Seconds (respectively) a reacquisition time of 0.1 seconds and supports standard NMEA-0183 and SiRF binary protocols. The hardware consists of SiRFstarIIe chipset with embedded ARM7TDMI

Figure 2. Motes were mounted on FDM-constructed chassis to facilitate field deployment.

microprocessor, an external antenna jack, 20 pin connector, and protective metal cover sheild, measuring 25.4 x 24.1 x 6.9 mm. The GPS unit is relatively expensive to operate. From a cold start, it requires 65 mA of power, then runs until the GPS reading is stabilized. When the sensor application is statically deployed, the GPS unit need only run until an accurate location fix has been obtained, at which point the GPS is powered off. For "dynamic" deployments, where the GPS unit is used for tracking the movement of fire fighters and equipment, the GPS sampling rates may be triggered by the amount of motion recorded by the unit, faster sampling resulting from highly mobile units.

The Intersema 5534AP is a low power integrated pressure sensor with pressure range 300-1100 mbar on a 15 Bit ADC. 6 coefficients for software calibration stored on-chip, which communicates 3-wire serial interface. The 5534 also measures temperature, providing a check on the temperature results from the Sensirion SHT11 sensor described next.

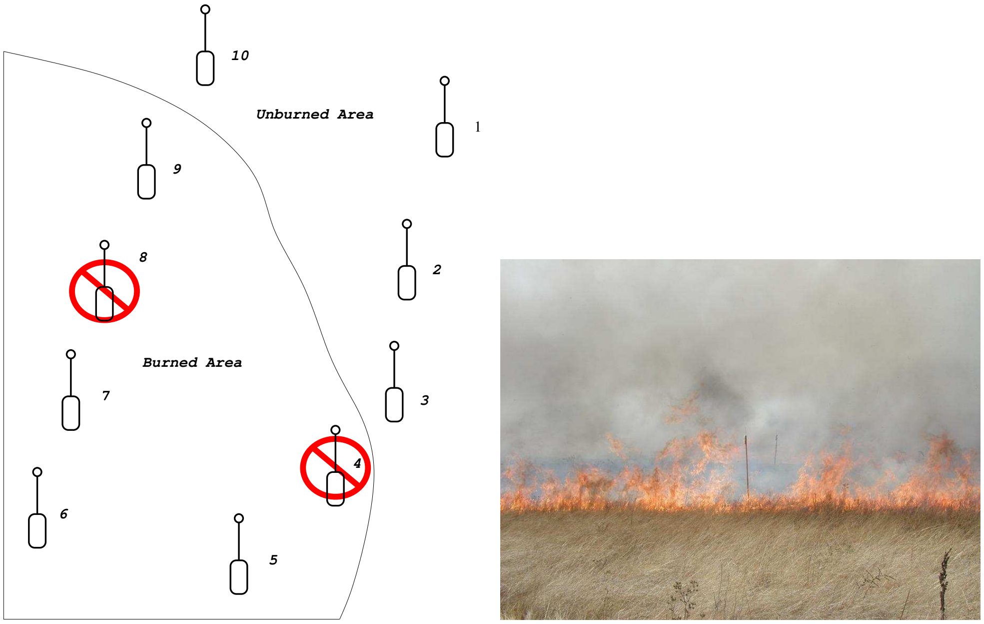
The Sensirion SHT11 temperature and humidity sensor is a single chip module providing calibrated digital output. Both instruments are coupled to a 14 bit AD converter and a serial interface for superior signal quality, fast response time and insensitivity to external disturbances. The relative humidity (RH) sensor is accurate to $\pm 3\%$ between 20-80% RH, $\pm 5\%$ outside of that range. The temperature accuracy is within $\pm 2.5^\circ$ C between -40° to 120° C.

For field testing, each mote was mounted on an FDM-constructed chassis, which helped protect the soldered connections on the mote (battery and antenna) from rough handling (Fig. 2).

2.2. Software

The Crossbow Mica2 mote may be operated using TinyOS, an operating system specifically developed for programming small devices with embedded microcontrollers. TinyOS provides a developer library for controlling radio and serial communication, and for operating various sensor boards connected to a mote. TinyOS is programmed largely in the nesC language, which was designed expressly for efficiently capturing the semantics of programming for small embedded devices. The biggest advantage of TinyOS is that application level code is independent of the underlying mote platform, thus changing platforms requires simply recompiling the application source code for the appropriate platform.

Using the `nesC` programming language and TinyOS operating system allowed the fire monitoring sensor application to be developed very rapidly. The project would have been much more difficult had coding the sensor application machine-specific assembler codes been required. For the sensor application, sensor driver code provided by Crossbow, Inc. was modified to implement a "High-level Sensor" interface (3), which provides a



(a) Layout for 10 motes. Motes 2, 4 and 8 were inoperable. Arrows show direction of flame travel.

(b) Flame front advancing on mote 5.

Figure 3. 10 Motes were tested during the September 16, 2004 prescribed burn at Point Pinole Regional Park, near San Pablo, California.

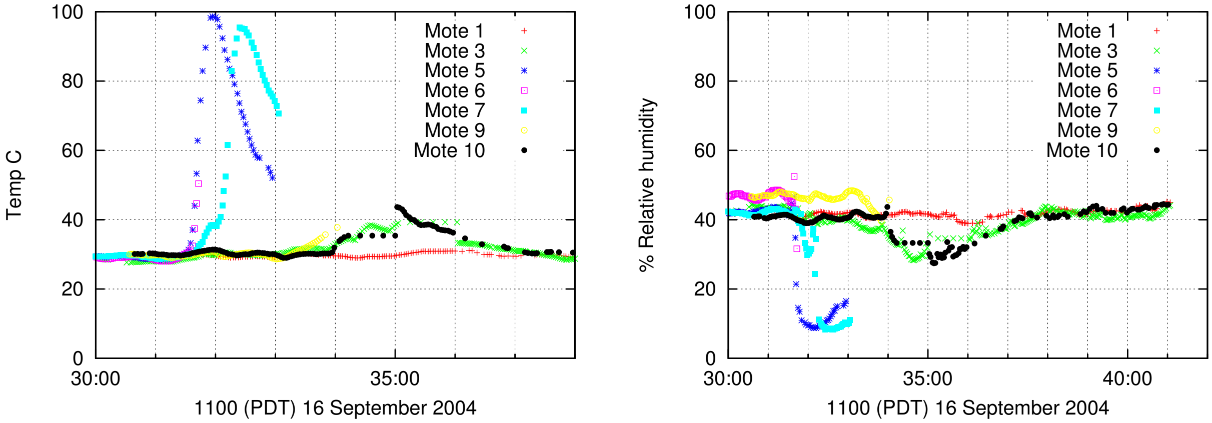
standard set of commands for controlling sensors. The sensor application was then written to handle events triggered from the underlying driver code.

3. FIELD TESTING

The initial field tests were performed to investigate proof of concept of the system and the robustness of the hardware in actual wildfire conditions. For practical purposes during field work, the base station, database server and client were operated from a single, daylight-readable Fujitsu tablet personal computer. Testing the wildfire monitoring system required close collaboration with the East [San Francisco] Bay Regional Parks Fire Department. Although, the field tests were performed under prescribed burn conditions in relatively low fuel load grasslands, these were full scale firefighting exercises requiring that all research participants be appropriately trained and certified (Type II wildland firefighter certificate). In addition, although the prescribed burn setting provided a fair degree of control over the deployment of instrumentation, it was essential that once deployed the instruments would operate with a fair degree of reliability. For this reason, the application loaded onto the motes was kept simple for the test, and much effort was expended rehearsing mote setup and data collection. As a result, useful data was gathered for both the test burns.

3.1. Results from prescribed burn September 16, 2004

The prescribed burn was conducted in a grassy area of light fuel, approximately one ton per acre, thus was not a very “hot” burn with respect to fires burning in areas with denser shrubbery or in wooded areas. The motes were staked on posts in order to maintain good visual contact and to maximize the reach of the mote radios (Figs. 2 and 3(b)). Data collected from the prescribed burn consisted of temperature, relative humidity, barometric pressure, and the resulting physical condition of the burned motes.



(a) Motes 5-7 clearly show a temperature response during passage of the flame front, while motes 3 and 10 record the proximity of the flame front. The fire was extinguished before it's effect on mote 1 could be measured. Mote 9 was scorched, and too little data were reported to allow quantitative assessment of the condition at mote 9 when it stopped working.

(b) Passage and proximity of the flame front as indicated by relative humidity data from the motes matches the temperature data: motes 5-7 were scorched, motes 3 and 10 were close to the flame front, and mote 1 is outside the effect of the flames.

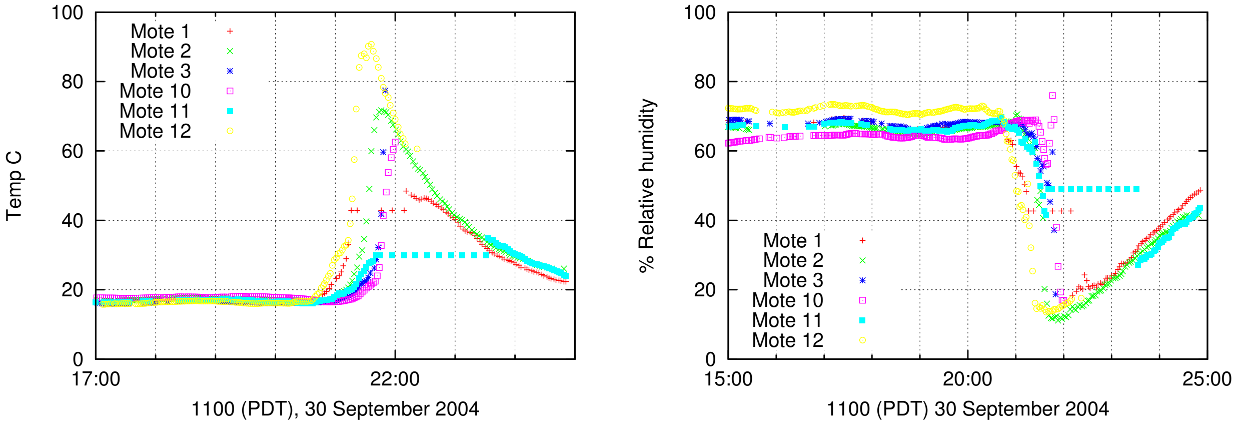
Figure 4. Temperature and humidity results from field testing September 16, 2004 at Point Pinole Regional Park, near San Pablo, California.

The mote chassis in the burned area (Fig. 3(a)) warped from the heat, and most of the battery cases partially melted. The motes and sensorboards did not show visible damage. Every mote in the burned area eventually failed to report data at some time during or after the flame front passage, for a variety of reasons. Motes 5 and 7 suffered melted battery casings, but still work when supplied with power. Motes 6 and 9 became completely unserviceable. Mote 8 suffered damage to the Molex battery connection before the test began, and did not record any data at all due to lack of power. Mote 2 reported only 0 values, possibly due to a poor 52 pin connection between the sensorboard and the mote, since this Mote performed successfully during the subsequent September 30th test. Mote 4, located inside the burn area, exhibited the same behavior, reporting only 0 valued data.

Figure 4(a) shows temperature data for motes 1, 3, 5, 6, 7, 9 and 10. As noted above, motes 2, 4 and 8 did not record data. Motes 4-9 were located in the burned area, motes 1-3 and mote 10 were located outside the burn area. For the scorched motes, the effect of the advancing flame front is obvious from temperature plots. Temperatures for motes 5 and 7 show a spike in the temperature, evidently surviving the hottest part of the flames to record post-peak temperatures before physically failing. As noted above, the battery cases for both motes 5 and 7 melted enough to lose power, but both motes are still otherwise serviceable. Motes 6 and 9 on the other hand, only record smaller increase in temperature before completely failing. Most likely, the temperature difference and gradient after the last recorded sample (at 11:31:43 am for mote 6, 11:34:02 am for mote 9) was large enough to induce physical failure of the mote. As noted above, neither mote 6 nor mote 9 remained serviceable, although each of the sensorboards will still operate on a serviceable mote.

3.2. Results from prescribed burn September 30, 2004

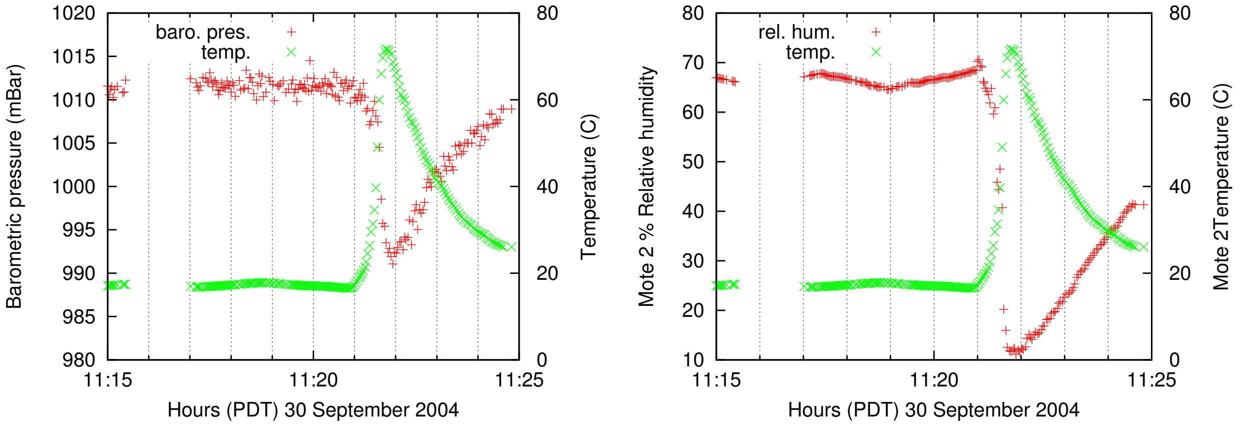
The results from the September 30, 2004 test are shown in Fig. 5. Motes 1, 2, 3 and 10 were reused from the September 16, 2004 test. The 51 pin connections on all motes were carefully checked, and the initial data was examined to ensure that each mote was returning valid results. In this prescribed burn, only mote 10 ceased to function completely for the duration of the test. However, motes 1 and 11 retransmitted the same packet for a 1 and 2 minute (respectively) period of time during the passage of the flame front, then started operating



(a) Temperatures recorded by the motes clearly show the passage of the flame front over time.

(b) Relative humidities recorded by the motes clearly show the passage of the flame front over time.

Figure 5. Temperature and humidity results from field testing September 30, 2004 at Point Pinole Regional Park, near San Pablo, California.



(a) Combined plot of barometric pressure and temperature showing mote 2 response during passage of the flame front.

(b) Combined plot of relative humidity and temperature showing mote 2 response during passage of the flame front.

Figure 6. Data recorded by Mote 2 on September 30, 2004.

correctly once enough heat dissipated. The cause of the behavior is not yet known, but it is likely hardware related since the sensor software responds to hardware signaled events. In the case of motes 1 and 11, the timing loop on the mote continued to operate even though no sensor events were handled, and the last known data sent on the timeout. Figure 6 shows the temperature plotted against the barometric pressure and the relative humidity for mote 2. The sensor response is excellent, data are recorded on approximately 2.5 second intervals. Data sequence numbers indicate very low packet loss.

3.3. Discussion

Comparing the temperatures from the burn conducted on September 16, 2004 (Fig. 4(a)) with temperatures recorded during the September 30 burn (Fig. 5(a)) shows the September 30 burn had significantly lower temperatures both at the initiation of the burn and for the peak temperatures. In contrast, the relative humidity on September 16 (Fig. 4(b)) was approximately 40-45%, which is much lower than the relative humidity of 60-65% recorded on September 30 (Fig. 5(b)). Since the fuel moisture content is a function of the ambient relative humidity, lower peak temperatures are most likely related to higher relative humidity than to lower initial ambient temperature.

The peak temperatures recorded during both burns were surprisingly low. One possible reason for this is that the response of the temperature sensor is roughly 2 seconds, inducing a temporal averaging effect into any reading. The temperature of the flame frame front varies chaotically, while the sensor responds to accumulated heat. Thus, while very brief applications of high heat may be enough to ignite the grassy fuel, the fire front moves rapidly enough so as not to allow the temperature sensor to record the rapid variations in point temperature.

Since the motes were deployed above (0.5 m) the top of the fuel to avoid radio transmission packet loss, the cooler temperature may indicate a rapidly decreasing temperature gradient with respect to height above the fuel. This possibility requires further investigation, as the motes were clearly exposed to flames at some point during the passage of the flame front, as shown in Fig. 3(b).

The exponential decay of the temperature after passage of the flame front indicates either stored heat dissipating from the entire sensorboard and mote system, or cooling of the burned area after the passage of the flame front, or both. However, recovery of the relative humidity and barometric pressure values should not necessarily be affected by the behavior of the sensor platform, and may indicate the local weather conditions around the sensor after the passage of the flame front. Figure 6(a) shows that the temperature after the flame front recovered to a higher value than the initial temperature during the approximately 4 minute time period required for the barometric pressure to return to it's initial value. Figure 6(b) shows that the relative humidity after the passage of the flame front is much lower than the initial condition.

The results from this initial, proof-of-concept field testing suggest many possible directions for future tests. Real time evolution of the fire could be better monitored by surveying the area to be burned and recording the exact time that the fire was started. This will require closer work with the firefighters, and more convenient base station setups.

Better flame and heat protection for the motes and batteries may allow longer data collection through the passage of the flame front. For example, in grasses and other light fuels similar to what was burned for the field tests at Point Pinole, wrapping the mote battery case with duct tape may be sufficient to prevent the battery from losing contact. Vertically arrayed motes as well as horizontally distributed motes would help provide a more detailed information on the actual structure of the flame front. The limitation on this is the radio operation at less than wavelength above absorbing boundary such as dry grass or fuel. To help prevent packet collision the motes could be arrayed at different vertical heights at different locations. Faster sampling, more robust sensors with a wider range in operating conditions would allow better calibration of fire models to predict the environmental conditions after the passage of the flame front, possibly allowing more efficient firefighter response.

4. SUMMARY AND CONCLUSIONS

The wireless sensor wildfire monitoring system represents a proof-of-concept implementation for wireless instrumentation in destructive, environmentally hostile wildfires. Results from field testing in light fuels indicate that the hardware performs adequately out of the box, increasing the economic viability of the system for commercial development. From discussions with fire fighters, a sensor that could only indicate the presence of fire would be useful, even if the instrument was rapidly destroyed. However, the actual performance of the sensor motes indicates that minor hardening of the battery cases would likely allow sampling through more of the passage of the flame front. In heavier fuels, the mote will need to be protected, while still allowing the sensors to operate accurately. For, inexpensive, disposable motes, we believe that adequate protection will be cost effective.

Using this system for wildfire monitoring has several advantages over traditional systems requiring wired sensors:

1. Individual motes are relatively inexpensive, allowing more data to be collected per unit cost;
2. Standardized, freely available and modular software components reduce cost of developing, modifying and maintaining the system;
3. The motes are easy to deploy and use;
4. The deployed system allows near real-time response to events such as rapid temperature rise reported by deployed sensors.

Longer term deployment of motes in fire-prone areas preceding wildfire events will require more sophistication in the data collection algorithms. For example, sampling could be conducted intermittently from motes usually suspended in sleep mode. The frequency of sampling could be tied to the current environmental state: high temperature with low humidity in the daytime would increase the frequency of sampling, the converse decreasing. Triggering sampling rate changes could be accomplished by inspecting the gradients, or by motes querying the gateway to request sampling parameters.

The construction of the wireless sensor monitoring system lends itself to incorporation within larger sensor data collection systems. For example, the SHIMS (4) project describes a sensor metadata repository useful for monitoring lifecycle changes to structures such as bridges and buildings. Combining a internally-focused structural sensor system with this system's externally-focused environmental sensor system provides wholistic coverage of a building system. The combined system is larger than either wildfire monitoring or SHIMS, and allows correlation between events (structural failure) and causes (direction of advancing flame front).

ACKNOWLEDGMENTS

We would like to thank the National Science Foundation for funding this work under the auspices of Information Technology Research grant ITR/IM-0121693. We also thank Chief Dennis Rein, Capt. Tim August, Lt. Mike Sweeney and Firefighter Brad Gallup and of the East Bay Regional Parks Fire Department for allowing us the opportunity to test the system under controlled burning conditions.

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