Experimental Investigation of "Smart Dust" for Pavement Condition Monitoring

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ABSTRACT

Pavement maintenance is vital for travel safety; detecting road weather conditions using a wireless sensing network poses many challenges due to the harsh environment. This paper presents some preliminary results of an ongoing effort to apply a "Smart Dust" sensor network for monitoring pavement temperature and moisture presence to detect icy road condition. Careful considerations yielded effective solutions to various hardware and software development issues including the selection of sensors and antenna, design of casing, interfacing motes with alien sensors and programming of motes. A series of experiments was carried out to study how traffic interference affected packet delivery performance of a small-scale sensor network in a pseudo-field environment. The results are analyzed and challenges are identified in this smart sensing application. The research activities will benefit robust real-world implementations of off-the-shelf sensor network products.

1 INTRODUCTION

Pavement maintenance is vital for travel safety and thus remains a major issue for transportation agencies nationwide. It is essential to provide warnings of dangerous traffic conditions such as wet and iced pavement in a real-time fashion. This project investigates a densely distributed sensor network technology, "Smart Dust", for its potential benefits in monitoring pavement conditions. The goal is to embed a proper algorithm into "Smart Dust" processors, which is developed to classify pavement surface conditions into four categories of (1) dry, (2) wet, (3) frozen, and (4) others, based on the measurements collected by "Smart Dust". In this paper, a preliminary ice detection algorithm was proposed to categorize pavement surface conditions based on these types of measurements, as shown in Fig. 1.

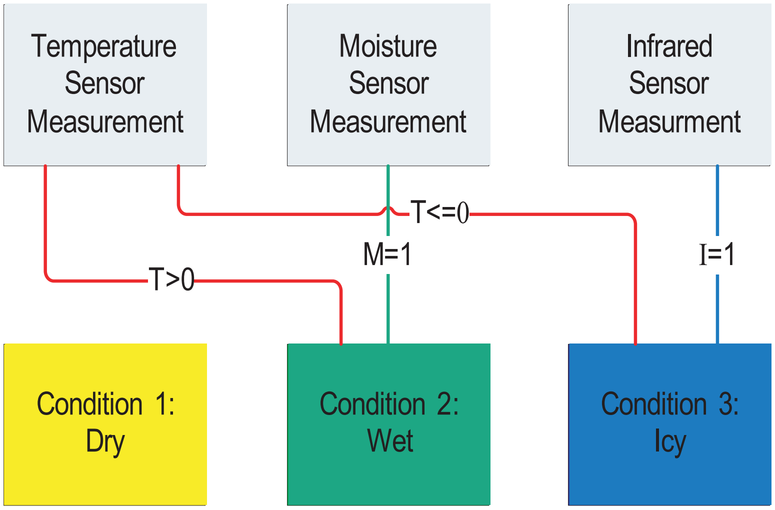


Figure 1: Proposed ice detection algorithm, where T, M, I denote the readings from the selected temperature, moisture and infrared sensors, respectively. In detail, T is the absolute reading of the measured temperature. $M = 1$ denotes the presence of moisture, and $I = 1$, the presence of ice.

2 LITERATURE REVIEW

In this study, the essential sources for “Smart Dust” are from Crossbow Technology Inc. [6] and the TinyOS online forum [2]. To carry out the proposed tasks, literature review was conducted focusing on transmission range, network stability and packet delivery performance of “Smart Dust” as well as application case studies of “Smart Dust”. Table 1 outlines some of these relevant publications.

Ref.	**Network Size**	**Application**	**Transmitting Range**	**Antenna Height**	**Sampling Rate**	**Carrier Frequency**	**Antenna Type**
[6]∗	256	N/A	1000 ft	N/A	19.2 Kbps∗∗	433 MHz	stock Mica 2 433 MHz (6.8 in)
[5]	55	lab testing	1 m	unspecified	1 Hz	unspecified	unspecified
[3]	2	outdoor in various conditions	10-55 m and lower	1 m above the ground	unspecified	900 MHz	stock Mica 2
[10]	40-60	inside an office building and outdoor	0.5 m	ground	1 Hz	433 MHz	omni-directional whip antenna
[4]	2	lab testing	unspecified (shown in the paper)	unspecified (shown in the paper)	15.625 Hz	916 MHz	stock Mica 2
[7]	20, 25, 34	outdoor and large-scale lab testing	unspecified	a wall and a beam	unspecified or 100 Hz	916 MHz	80 mm long copper wire
[8]	1	lab testing	unspecified	unspecified	unspecified	916 MHz	stock Mica 2

Table 1: Some applications using motes and their testing Configurations.
∗ Information cited from [6] follows the maximum values provided by the Crossbow Technology Inc.
∗∗ Maximum transmission rate.

3 SELECTED SENSORS

Based on the proposed algorithm to detect the existence of ice, three types of “alien” sensors were selected to be interfaced to “Smart Dust” (consisting of Mica 2 motes in this study). With many possible choices at hand, main factors in selecting these sensors are *cost*, *power consumption*, *size*, and *durability*. As shown in Fig. 2, the final selected sensors for this project are:

Thermistor This 10 KΩ thermistor is used to take temperature reading.

Leaf Sensor This moisture sensor detects the conductivity of a wet pavement so as to detect the existence of free moisture.

Infrared Sensor This infrared sensor is composed of an infrared emitter and receiver of same infrared wave length. The infrared sensor detects ice by emitting a near infrared light that is reflected by the ice and detected by the infrared receiver. Note that water is transparent to the infrared sensor.

Figure 2: Selected sensors: (a) A thermistor, (b)a leaf sensor, and (c) an infrared sensor

These three sensors used three input channels (two digital and one analog) and one output (used to power the sensors) from the mote.

4 HARDWARE INTERFACE

The hardware interface refers to the one that connects a mote to the sensors; an overview of the hardware interface is presented in Fig. 3. An integrated sensor and road button structure, called a "sensor-road button", houses the three sensors as shown in Fig. 3(a). The top surface of the sensor-road button contains the moisture and infrared sensors, and the bottom, the thermistor. Such a sensor-road button prototype was merely for testing purposes; the final product would be made to withstand high speed traffic and harsh road conditions. An MTS101 prototyping board as shown in Fig. 3(b) was used to ease the connection of the sensors to a mote. All the sensors were able to be powered by the mote due to their low power consumption. Each sensor was then connected to the MTS101 board through a simple circuit that furnished the correct voltage to control the sensor.

Figure 3: Hardware interface: (a) a "sensor-road button" prototype with the selected three sensors, (b) a prototyping/connection board, and (c) a Mica 2 mote in a casing with a selected antenna.

The MTS101 board was then placed on top of the mote after being connected to the sensor-road button through a shielded wire, which protected the circuitry from any external interferences. As shown in Fig. 3(c), the MTS101 board and a Mica 2 mote were placed into a casing. The water-tight aluminum casing was a carefully selected off-the-shelf product integrated with an upgraded antenna. Mica 2 motes come equipped with a "primitive" quarter wave length antenna consisting of a wire sticking out of the mote with a swivel connection. Since this connection was reported to be unstable and the antenna to have bad transmission/reception capabilities [3, 10], a permanent studmount 1/4-wave whip antenna model ANT-418-PW-QW Linx Technologies, Inc. [9] was selected as a replacement antenna, connected to the mote with an MMCX connector and customized to fit on the top of the casing. The aluminum casing also acted as a reflecting ground and simulated a dipole effect thus doubling the motes transmitting range [6].

5 SOFTWARE INTERFACE

The software implementation refers to programming motes to take readings from input ports and transmit them. In accordance with the low power constraint of this project, *Surge Time Synchronization* was adopted because it enables the motes to sleep and only turns them on at the time when data transmission occurs from other motes. The other candidate, *Surge Reliable*, was not adopted since it is mainly used for data transmission and consumes more power. A modified version of *Surge Time Synchronization* was developed in this project, which was able to wake up, refresh the motes, take readings from all three sensors, digitize the readings, and finally transmit the data to the parent motes [6]. The information and logic flow in the system are shown in Fig. 4.

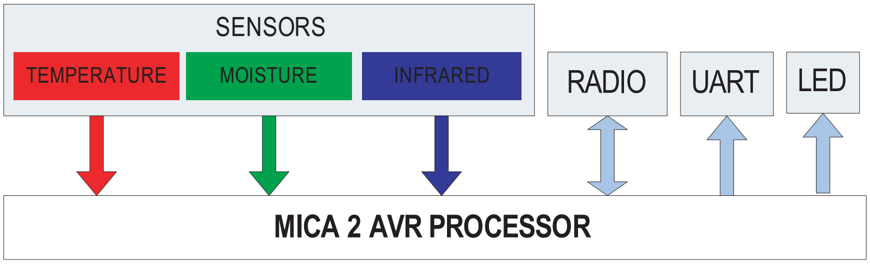
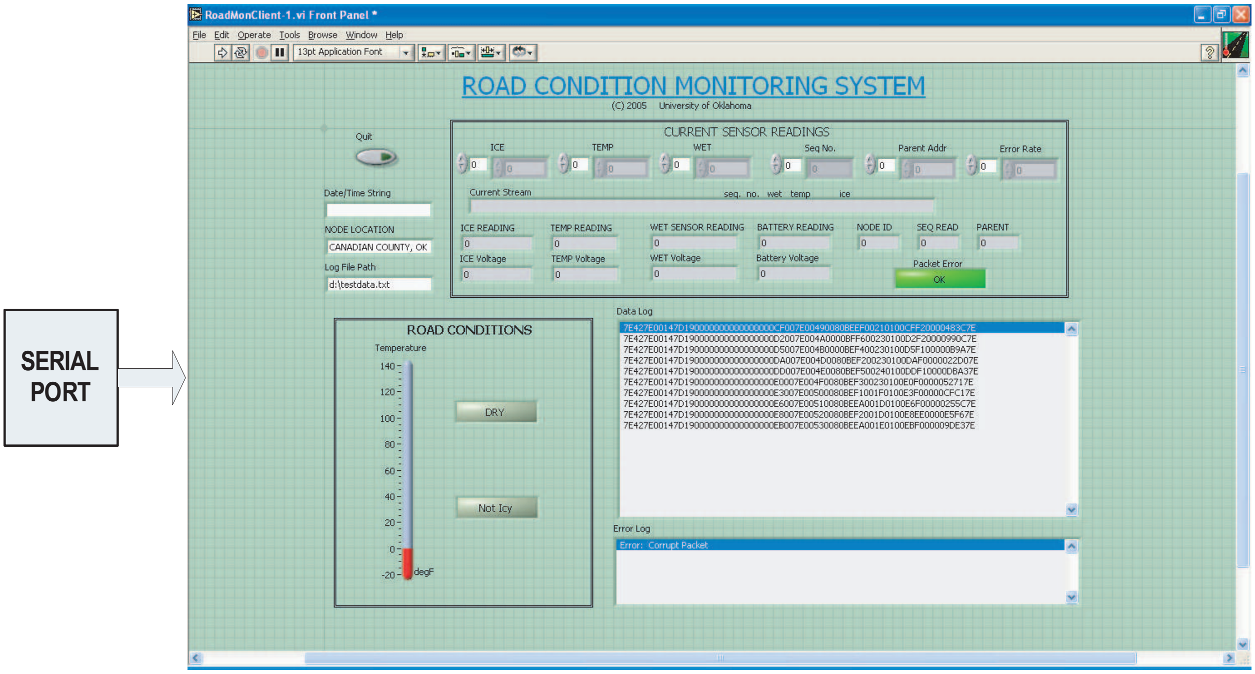


Figure 4: Information flow logic.

Under *Surge Time Synchronization*, motes were ready to read the inputs from the sensors into the motes after being woken up. Once the readings were taken, the mote transformed them into digitized data, sent them to the radio and waited until all data was sent before switching to sleep mode. In detail, the processor received sensor readings from the embedded 10-bit Analog-to-Digital Converter (ADC). If the data was taken correctly, the onboard light emitting diodes (or LEDs) lit up to signal the proper functioning of the mote. Analog to digital conversion was performed on the readings, after which the data was integrated into the packet to be transmitted. The default packet format was slightly modified to fit the size and format of the data to be transmitted. For example, the on-board temperature was replaced by the “alien” moisture reading. The packet was then sent to the radio and transmitted over the network until it reached the base station. The base station was connected to a laptop through a serial port. The data is then collected using a LabVIEW graphical user interface (GUI) developed in this project as shown in Fig. 5. Raw data from the serial port was collected, deciphered and displayed by the GUI. If an error was detected, it was displayed and saved into an error log file, while the collected correct data was saved into a separate file.



Date/Time String

NODE LOCATION: CANADIAN COUNTY, OK

Log File Path: d:\testdata.txt

ICE: 0 0
TEMP: 0 0
WET: 0 0
Seq No.: 0 0
Parent Addr: 0 0
Error Rate: 0 0

Current Stream — seq. no. wet temp ice

ICE READING: 0
TEMP READING: 0
WET SENSOR READING: 0
BATTERY READING: 0
NODE ID: 0
SEQ READ: 0
PARENT: 0
ICE Voltage: 0
TEMP Voltage: 0
WET Voltage: 0
Battery Voltage: 0
Packet Error: OK

Data Log

```
7E427E00147D19000000000000000000CF007E00490080BEEF00210100CFF20000483C7E
7E427E00147D19000000000000000000D2007E004A0000BFF600230100D2F20000990C7E
7E427E00147D19000000000000000000D5007E004B0000BEF400230100D5F100000B9A7E
7E427E00147D19000000000000000000DA007E004D0080BEF200230100DAF0000022D07E
7E427E00147D19000000000000000000DD007E004E0080BEF500240100DDF10000DBA37E
7E427E00147D19000000000000000000E0007E004F0080BEF300230100E0F0000052717E
7E427E00147D19000000000000000000E3007E00500080BEF1001F0100E3F00000CFC17E
7E427E00147D19000000000000000000E6007E00510080BEEA001D0100E6F00000255C7E
7E427E00147D19000000000000000000E8007E00520080BEF2001D0100E8EE0000E5F67E
7E427E00147D19000000000000000000EB007E00530080BEEA001E0100EBF000009DE37E
```

Error Log

```
Error: Corrupt Packet
```

Figure 5: LabVIEW GUI developed in this study for data collection at the server end.

6 LABORATORY TESTING OF SENSORS

A series of laboratory tests was conducted at the Asphalt Laboratory at the University of Oklahoma using an environmental chamber to study the effect of temperature and moisture on the sensors (and later, the motes). The environmental chamber was used to produce well-controlled temperature and humidity variations. The sensor-road button unit shown in Fig. 3(a) was tested, the results of a thawing process were presented in Fig. 6. The test was performed to (1) test the full functionality when all the sensors were combined together, and (2) collect data to aid refinement and further development of the proposed ice detection algorithm shown in Fig. 1.

The entire test shown in Fig. 6 was completed in a four-hour time frame. Note that weather changes in reality could be much slower than this testing rate; thus such a test could be more stringent than a real-world situation. Three zones in Fig. 6 can be identified. In Zone I (the area on the left of the blue dashed line), the sensors detected ice without the presence of water while the infrared and moisture sensors' voltage outputs were high. In Zone 3 (the area to the right of the green dashed line), the sensors detected the presence of water without ice while the infrared and moisture sensors' voltage outputs dropped and stabilized. In Zone 2 (the area between the blue and green dashed lines), the sensors detected a mix of ice and water while the infrared and water sensors voltage outputs dropped erratically. These results validate the proposed ice detection algorithm shown in Fig. 1. It also demonstrates the need to collect more data, especially those from the moisture and infrared sensors to form proper decision boundaries to implement the proposed ice detection algorithm.

Figure 6: Sensor voltage readings from moisture and infrared sensors vs. measured temperature in a thawing process.

7 PRELIMINARY FIELD TESTING OF "SMART DUST"

To understand the performance of "Smart Dust" in a high traffic environment, preliminary tests were conducted since the summer of 2005 to simulate traffic interference and study how it would affect the packet delivery performance of the "Smart Dust" sensor network. Two major programs were used separately in a series of network tests, and they are *Surge Reliable* and *Surge Time Synchronization*. All the tests were performed in the vicinity of the Fears Structural Engineering Laboratory (abbreviated as Fears Lab thereafter), an open-space at the campus of the University of Oklahoma with some low-rise buildings, several large trees, and a generally very low traffic volume. In such a testing environment, traffic interference could be introduced almost at a totally controllable manner by driving a truck at a speed of about 15 mph. Throughout this study, a small sensor network was formed with four motes. All the tests were conducted under a weather of sunny to cloudy. A typical test setup is presented in Fig. 7.

The software of *Surge Reliable* was merely used for testing network capability and transmitting ranges in this study, when the default data acquisition GUI was used. Following the packet loss analysis in [3], a series of transmitting range tests using the *Surge Reliable* algorithm running at the

Figure 7: Test setup when (a) six-foot high steel posts and (b) thirty-three-inch high timber posts were used. (c) A map showing the layout of motes and the driving route to introduce traffic interference.

maximum transmission power was performed. The separation distance of two motes was found to be 250 and 200 ft with the height of motes at 6 ft and 33 inches, respectively. In addition to these transmitting range tests, all four motes were lined up to form a straight line as shown in Fig. 7(c) to perform traffic interference tests while varying the interval from 100, 150, 200 to 250 ft.

As a procedure adopted in all of the tests, all of the motes were turned on one by one and then left for initialization for half an hour to an hour before any data was collected. After such a waiting period, however, not all the motes could always be detected in the default *Surge Reliable* GUI, which led to some "debugging" effort on site, e.g., reassuring good connections at each mote, turning off all the motes and restarting all of them at the base station before placing individual motes back to the field. Fig. 8 presents one set of the complete test results using *Surge Reliable* after the network was "debugged", when the distance between two adjacent motes was 100 ft and the height of the motes was fixed at six feet. The 30-minute control test with the presence of traffic was introduced by driving the truck 10 times following the driving routes shown in Fig. 7(c). Shown in Fig. 8 are the time histories of (a) the sequential number of the received packets, (b) errors (which refer to repetitive consecutive sequential numbers received at the same mote) [1], (c) yield (i.e., the cumulative ratio of packet received and packet sent) and (d) parent. Note that the shaded interval of traffic interface is indicated roughly on the time history plots. From this set of the results, the interference from traffic is not clear, while the error and data loss are fairly outstanding.

The software of *Surge Time Synchronization* was further tested using the GUI developed in this project (see Fig. 5). With a mote interval of 100 ft, the tests were conducted under a configuration similar to that using *Surge Reliable*. A correct network hierarchy was expected to be that Mote 0 parents Mote 1, Mote 1 parents Mote 2, etc. (see Fig. 7(c) for the mote IDs). On many occasions, the motes would not be connected together in the expected way. For example,

- The synchronize time was at least 20 minutes for the first mote to connect to the base station.
- Very often, motes could be disconnected from the network at random times without any external interference.
- On several occasions, a mote would fail to connect to the network, even when the network was repeatedly reset.

To overcome this connection problem, several setup procedures were exercised in the field tests, however, none of these always guaranteed to work. These procedures are summarized as follows:

Procedure 1 : Place all the motes in the field and then turn them on approximately all at once.

Procedure 2 : Place Mote 1 out in the field, turn it on and wait for it to connect to the base station (Mote 0). Then place Mote 2 and wait for it to connect to the network, etc.

Procedure 3 : Turn on all the motes at the base station. Wait until all the motes connect to the network, and then place individual motes to the field.

8 CONCLUSION

In this study, efforts have been made to interface “alien” sensors to “Smart Dust” Mica 2 motes. Several hardware and software interfacing issues and proposed solutions have been discussed in this paper, which shows the potential of applying this off-the-shelf sensor network for robust real-world applications. Preliminary field tests of networking performance, however, have revealed the complexity of this off-the-shelf product and challenges in real-world implementations. More tests and analysis are being carried out in this ongoing study.

9 ACKNOWLEDGMENTS

This project is primarily sponsored by the Oklahoma Transportation Center. The grant from Research Council at the University of Oklahoma is greatly appreciated. The technical assistance offered by Mr. Michael F. Schmitz throughout the project is deeply appreciated. The assistance offered by Mr. Yohanes P. Sugeng in preparing the steel posts and Mr. Chase Sandburg in assisting the transmitting range test in the summer of 2005 is also acknowledged.

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