Wireless Sensors for Automated Control of Total Incombustible Content (TIC) of Dust Deposited in Underground Coal Mines

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Abstract— This paper presents ongoing research towards a low-cost/low-power wirelessly enabled distributed sensing system that can be placed throughout underground coal mines to potentially measure the total incombustible content (TIC) of the deposited dust. Underground coal mining operations produce finely divided coal dust, called float dust, which deposits throughout the mine. This combustible material can be feedstock for coal dust explosions. In the U.S., Mine Safety and Health Administration (MSHA) standard 23789 dictates that a TIC of 80% or above has to be maintained in coal mine return airways. However, current best practices for collection TIC measurements involve manual sampling and laboratory procedures. In this work, we describe work towards developing a new wireless sensor network (WSN) consisting of low-cost/low-power sensor modules that use a variety of optical and microfabricated sensors to ***continuously*** monitor the TIC of the accumulated dust. The information is then transmitted off-board through a reliable ad-hoc wireless network. Called Sensors for Automated Control of Coal Dust (SACCD), this system can potentially, for example, be used to automate the control of rock-dusting equipment to maintain TIC at acceptable levels.

Keywords—Float Dust, Wireless Sensor Networks, Total Incombustible Content

I. INTRODUCTION

Underground coal mining operations produce finely divided coal dust, called float dust that deposits throughout operating coal mines. This combustible material can be feedstock for coal dust explosions, and current mining operations produce finer and more easily combustible particles than was the case in the early twentieth century [1]. Limestone powder, known as rock dust, is used widely as an inerting agent, and mine safety regulations specify minimal total incombustible content (TIC) for both intake and return airways. These limits ensure that the dispersed coal dust to rock dust mixture will not propagate a flame in air.

Several optical methods to detect the TIC exist, such as the Optical Dust Deposition Meter (ODDM) [2] and the Coal Dust Explosibility Meter (CDEM) [3]. These methods assess the TIC of coal and rock dust mixtures deposited on surfaces of underground mines. These devices, although effective, are quite labor intensive and depend on moisture content of the mixture.

II. SENSING ELEMENT DESIGN

The SACCD consists of an optical dust reflectance-based sensor, a microfabricated moisture sensor, and a MEMS mass sensor. A close-up partial cutaway rendering of the sensing elements of the SACCD prototype is shown on Fig 1.

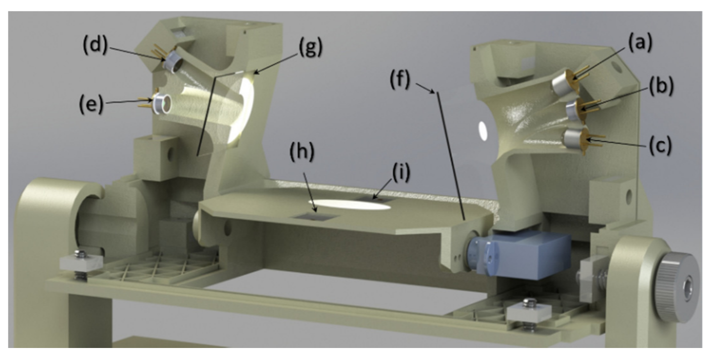

Figure 1: Partial cut-away CAD drawing of the sensor module indicating (a) probing optical transmitters, (b) calibration detector, (c) reference transmitter, (d) investigation detector, (e) reference detector, (f) quartz polka dot beam splitter, (g) clear quartz window, (h) microfabricated interdigitated capacitive moisture sensor, and (i) MEMS capacitive mass sensor.

A. Optical Float Dust Deposition Sensor

The operation of the optical dust deposition sensor is based on the difference in optical reflectivity of coal (black and low reflectivity) and rock dust (white and highly reflective). The optical dust deposition sensor determines the surface loading density of a dust layer by measuring its optical reflectivity.

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The degree of combustion hazard associated with float coal dust is related to the surface density of the deposited coal dust. The mathematical expressions for the normalized optical reflectivity for a layer of coal (rock) dust deposited over an optically thick layer of rock (coal) dust Φ_{cd} (Φ_{rd}) are given by [3],

$$\Phi_{cd} = e^{-\alpha_{cd}\sigma_{cd}} \quad (1)$$
$$\Phi_{rd} = 1 - e^{-\alpha_{rd}\sigma_{rd}} \quad (2)$$

Where σ_{cd} and σ_{rd} are surface loading of coal and rock dust respectively in mg/cm^2. Also, α_{cd} and α_{rd} are the attenuation coefficients associated with coal and rock dust respectively. The attenuation coefficient is a function of the optical characteristics of the individual particles and the particle size distribution.

Fig. 1 shows the optical dust deposition sensor setup which consists of a probing infrared LED light source (a), and an infrared phototransistor detector (d) to measure the reflectance from the mixture of coal and rock dust. To compensate for the change in intensity of the probing transmitter, the light beam is split using the microfabricated perforated beam splitter depicted in Fig. 2 and the intensity of the reflected part of the beam is measured using the calibration detector (c).

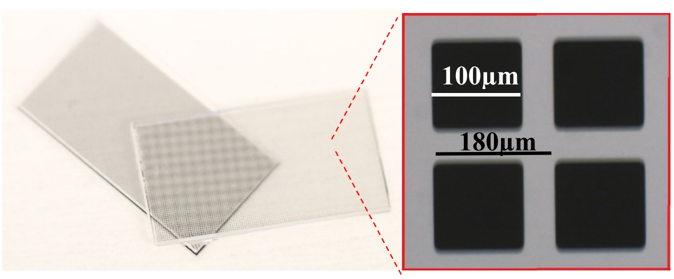

Figure 2: Microfabricated perforated (also known as Polka-Dot) beamsplitter fabricated by lithography patterning of deposited aluminum coating on quartz wafer. The beamsplitter is designed to 50:50 transmission to reflection ratio.

In addition to the interrogating beam, the reference beam (c) that crosses the optical detector (without interrogating the accumulated dust stack) provides reference data to track time-dependent changes of the beam intensity. In order to protect and counteract the fouling of the optics due to dust accumulation, we applied a hydrophobic coating to the quartz windows on both sides of the optical detector.

B. Interdigitated Dielectrometry Moisture Sensor.

The optical dust deposition sensor determines the mixture's TIC by measuring its near-infrared reflectivity. The surface reflectivity is also a function of the unbound moisture content of the mixture. To avoid the need for drying out the moisture before the measurement and to accurately measure the mixture's TIC, it is necessary to determine the amount of moisture present and then correct for it.

One of the most effective indirect nondestructive means for examination of moisture content of a material under test is dielectrometry. Interdigital dielectrometry sensors use fringing electrical fields between the electrodes to probe the material under test. These fringing field sensors do not require two-sided access to the MUT, unlike parallel-plate sensors. Fringing electric field lines pass through the MUT; as a result, the capacitance and conductance between the two electrodes depend on the material dielectric properties as well as the electrode and material geometry. The penetration depth of the fringing electric fields above the interdigital electrodes is proportional to the spacing between the centerlines of the sensing and the driven fingers [5].

To be able to probe a 1 mm thick mixture, the interdigitated sensor with spatial wavelength of 1 mm is designed and microfabricated by lithography patterning of an aluminum coated quartz wafer. Fig. 3 shows the design of the interdigitated moisture sensor as well as the results from finite element modeling of the sensor.

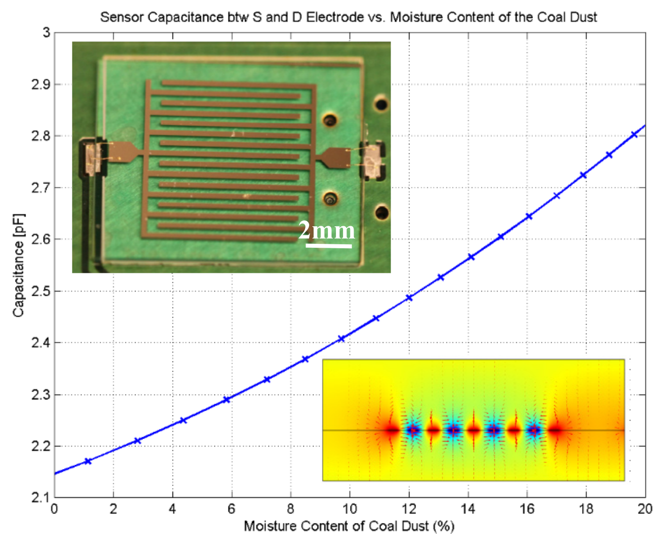

Figure 3: FEM modeled output capacitance between the drive and sense electrodes versus the moisture content of the coal dust. The insert shows the electrical field and potential distribution. The top-left insert is a macro image of the microfabricated moisture sensor wire-bonded to a PCB substrate.

C. Capacitive Mass Sensor

Due to the open structure and real-time nature of the SACCD, in which the system is continuously recording the accumulating dust layer, the surface of the sensor is expected to accumulate substantial amounts of float and rock dust. In order to measure the mass and gain additional information about whether rock or float dust is accumulating, as well as identify the level of accumulation for reconditioning /cleaning off the accumulated dust, a mass sensor that weighs the accumulating stack is needed.

The new mass sensor uses a modified design based on this group's previously fabricated MEMS capacitive in-line flow sensors [4]. The mass sensor uses the displacement of a paddle caused by the weight of the deposited coal and rock dust to induce a capacitance change between two ports of the sensor.

Simplicity of fabrication, low operating voltage (leading to an intrinsically safe design) combined with insensitivity to variations in ambient temperature, make this sensor ideal for widespread deployment in underground coal mines.

Fig. 4 is a macro picture of the MEMS capacitive mass sensor, fabricated using MEMS Silicon-On-Insulator (SOI) technology. A paddle supported by two cantilevers deflects out-of-plane under the weight of the mixture of rock and coal dust. Variable comb drive capacitors with movable electrodes attached to the paddle change capacitance as the structure is deflected. By measuring the change of the capacitance, the weight, and as a result, mass, of the stack can be calculated.

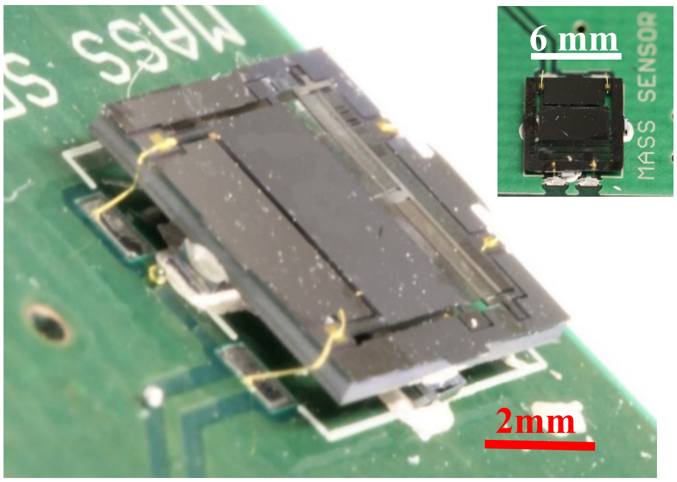

Figure 4: A macro image of the microfabricated mass sensor. Wire-bonds are visible, connecting the sensor electrically to the PCB substrate. Note that the sensor is elevated on pedestals to allow for the deflection of the paddle due to mass loading.

Using a 70 µm SOI thickness, the capacitance changes about 0.14 pF for 10 mg dust mass deposition on the paddle. Fig. 5 shows numerical modeling results for the change in capacitance of the mass-sensor as a function of the mass added to the sensor.

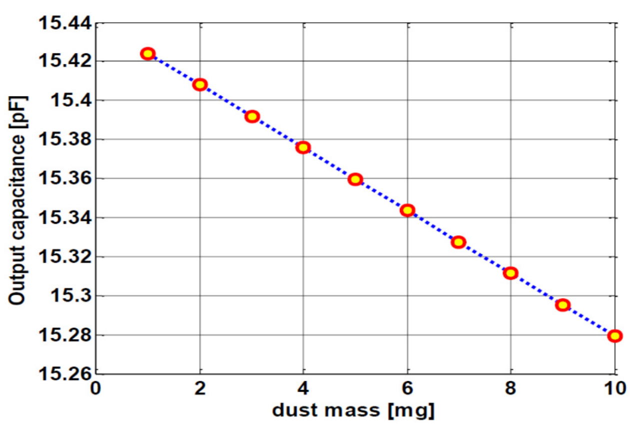

Figure 5: FEM modeled output capacitance vs. dust mass for MEMS flow sensor with SOI thickness of 70 µm, beam width of 50 µm, capacitor finger gap of 10 µm. Output capacitance changes about 0.14 pF for 10 mg dust.

III. Communications and Network

The hardware platform for the wireless mesh network has been selected as the Xbee DigiMesh network [6]. This platform provides safe networking, ease of deployment, variable power usage/transmission range profiles for nodes, as well as allowing the entire network to enter a deep-sleep mode to conserve power. In addition, all the nodes fulfil the same functions, which enables the network to reroute a signal should one node be damaged (e.g. destruction due to heavy machinery collision). Initial experiments show transmission ranges between the nodes in excess of 1000 ft in clear space. Initial experiments also show that the range can be further extended by placing the nodes in proximity to a conductor.

The data from all the nodes are collected by a central node, which is always awake and therefore always “listening” for transmit-request messages from every other node in the network. After having received a packet of data, the central node exchanges information with a laptop through a serial port. The process of collecting data from the serial port and then translating them in order to make them useful for the user is performed by means of a Python script running on the main computer.

IV. Experimental Results

An apparatus consisting of a 1.5 m high 15.24 cm diameter section of stove pipe is placed inside a portable glovebox with controlled humidity. To prepare a dust layer using this apparatus, an accurately weighed quantity of dust is placed in the dust reservoir and dispersed upward by means of compressed air. A petri dish is placed on the sensor platform at the base of the stove pipe to catch the settling dust. The petri dish is weighed before and after deposition of the dust for calculation of the surface loading density. The dust deposition setup is capable of dispersing both coal and rock dust over a humidity range from 10% - 90% RH. Pittsburg Pulverized Coal (PPC) with a mean particle diameter of 61.3 µm (S.D. 43.8 µm) is used to test the optical dust deposition sensor.

Fig. 6 shows experimental results from the optical reflectance of accumulated stacks of coal dust at different humidity levels. The results show good agreement with the Beer-Lambert law for deposited particles and strong dependence on the humidity level.

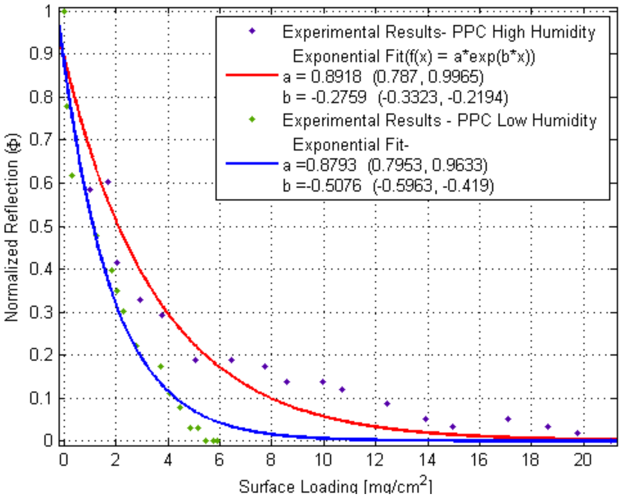

Figure 6: Experimental results showing normalized reflection from coal dust on a white substrate obtained using a functionalized optical sensing element prototype. Blue and green dots are experimental results from PPC coal dust under high (RH %85±5) and low (RH %30±5) humidity conditions inside the coal deposition chamber, respectively. Red and blue lines are exponential fit to the recorded data.

V. CONCLUSIONS

In this paper, we present work towards a low-cost/low-power wirelessly enabled distributed sensing system that can be placed throughout the mine to potentially continuously monitor TIC of the dust that is being deposited throughout the mine. The distributed sensors will use continuous optical, gravimetric, and dielectrometry methods to measure the TIC of the deposited stack of float dust/rock dust as well as the moisture content and the mass of the deposited stack. Low power design has been employed to enable the sensors to operate for extended periods of time underground without the need for changing their batteries. The sensors have been designed to periodically refresh their surface as well as mitigate the dust accumulation in the optical path. Experimental results from testing the sensor prototypes in a realistic test bed subjected to the deposition of the coal dust/rock dust mixture at different humidity levels are presented.

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