Decoupled Temperature and Moisture Sensor Made of CNT-Based Nanomaterials on Flexible Plastic Substrates

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ABSTRACT

In this paper, we report a successfully invented, prototyped, and characterized decoupled temperature and moisture sensor made of CNT-based nanomaterials on flexible plastic substrates. The detailed design of sensing elements, electronics hardware, and software are presented here. We tested the humidity sensor in constant temperature and in increasing temperature modes in a Espec BTL-433 humidity chamber. The measured results were compared to those collected by an Omega RHT HX71 series sensor. We discovered that our sensor can measure humidity independently of temperature, and it can also detect moisture from human breath. Preliminary results of temperature sensing are also presented.

Keywords: humidity sensor, temperature sensor, carbon nanotube electronics, microsystems, organic flexible electronics

1. INTRODUCTION

Materials based on carbon nanotubes (CNTs) have unique properties suitable for environmental sensing applications.[1-4] We have developed individual temperature and moisture sensors using CNT-based materials developed in-house on flexible polyethylene terephthalate (PET) and Kapton® substrates. Often, sensors are subject to multiple environmental variables, such as temperature and humidity, at the same time. The output signals bear the signatures of both input temperature and input humidity, making it difficult to use such output signals for process control and signal integration. In this paper, we report the development of an integrated temperature and humidity sensor that decouples the humidity signal from the temperature signal.

2. SENSOR SYSTEM DESIGN AND PROTOTYPING

2.1 Sensing Element Design and Fabrication

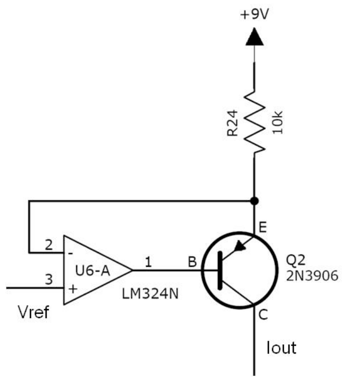
The basic sensing element is made of a silver interdigitated electrode (IDE) structure with a top coating of a functionalized CNT film. Silver IDEs were printed using an ink-jet printer. The coatings, produced from materials containing functionalized CNTs, were printed on top of silver IDE structures using an aerosol printer.

The moisture sensor is based on resistance change in the IDE structure. For the prototyped humidity sensors (H-sensors), a resistance change of more than 20% was observed at room temperature with a 30% change in humidity. The resistance changes were displayed on an LCD panel and on a laptop computer using our software. The temperature sensor was also based on the resistance change of the IDE structure. A resistance change of more than 2% was observed when the sensor was exposed to a temperature increase of 10°C from room temperature.

To decouple the temperature signal from the humidity signal, an integrated sensor platform was designed and tested. It was discovered that the humidity signal could be decoupled from the temperature signal completely.

2.2 Sensor Electronics Design and Prototyping

The electronic design for the CNT H-sensor electronics utilizes a constant current compensated or relative measurement design capable of measuring $\Delta R/R$ in the 10-20% moisture sensitivity range of the CNT H-sensor. This electronic system is not similar to the more precise auto-balanced bridge design and instead uses simple operational amplifiers in the configuration shown below. This design is capable of producing a high-precision constant current, Io, over a wide range. The sensor is connected between Io as shown in the figure and ground.



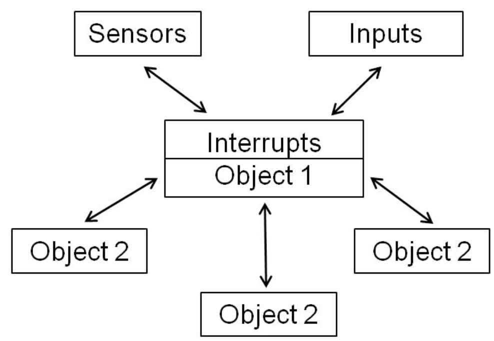
The constant current is produced by biasing the base of the transistor so that the voltage Vref in the figure is also present on the collector, which means that the current through the collector resistor is by definition (+9 V – Vref)/10 kΩ and upon inspection has nothing to do with the load voltage or impedance. Given this collector current and the negligible base current, then Io must be equal to the collector current and independent of the load or sensor impedance or voltage. That is, the design produces a constant load current through the sensor. Use of a FET in its linear region as a replacement for the bipolar transistor in the circuit would make an even more precise constant current source by further reducing the gate current to vanishingly small values.

The hardware uses two of these circuits, one driving the sensor current and another driving a temperature-compensated metal film resistor in close physical proximity to the CNT H-sensor. A standard instrument amplifier derived from three operational amplifiers is then used to measure the difference in voltage across the H-sensor and the standard resistor. As a change in humidity is present at the H-sensor, the resultant change in impedance is reflected as a change in voltage across the sensor when compared with the standard resistor. This voltage is signal conditioned for maximum resolution in a 12-bit analog-to-digital converter (ADC) circuit. The software measures the state of the ADC as a function of time and produces a real-time graph of the humidity signal present at the sensor.

The total noise in this circuit design is controlled by filters at the inputs of the instrument amplifier. These filters have a time constant of 10 msec, indicating a band pass of 100 Hz. Therefore the circuit is capable of measuring humidity transients as fast as 10 msec, seemingly much faster than the real environmental humidity could actually change. Power line 60-Hz noise is canceled through taking the difference between the standard resistor and the H-sensor, and generally noise accounts for less than 0.1% of the signal in the analog spectrum. Noise present in the software is of the bit-noise variety as a result of the limited 12-bit ADC resolution. That is, the analog signal has less noise present than that introduced by the digital ADC converter.

2.3 Sensor Software Design and Prototyping

The software is completely object oriented and interrupt driven. Its general outline is shown in the figure below. The objects are defined by the series of drivers required for communication, display, hardware, and data logging. The objects may themselves contain other objects in a hierarchy that allows for simple updating when specific drivers are changed.



That is, if the ADC driver and type is updated or changed to a different type, the new driver can be replaced with equivalent functions within a relatively small part of the program, and such a change does not influence the operation of all of the other objects in the program. In fact, the new object can simply be re-compiled by itself and linked to the other objects. Specific implementation of the program was accomplished by using open source g++ (C++) running through X-Windows server in Cygwin for Microsoft Windows® platforms, Linux, and OSX. The program utilizes open source Qt-3.0 libraries for the graphical user interface (GUI) and USB exo-drivers for the hardware interface.

The primary interrupts used in the execution of the program are timer interrupts that are used to generate signals for ADC data acquisition from CNT H-sensor hardware and logging the data to a standard text-based file structure. Other interrupts include those from the GUI, specifically, the keyboard, and mouse. The data acquired to plot on the screen is collected every 500 msec from 0.0 to 100.0 seconds, and data are logged every 5.0 seconds. All of these parameters can be easily modified in the program for the specific need of the experiment. Indeed we hope this general software platform can be used for a range of sensor and instrument platforms in the future.

3. CHARACTERIZATION OF HUMIDITY SENSOR

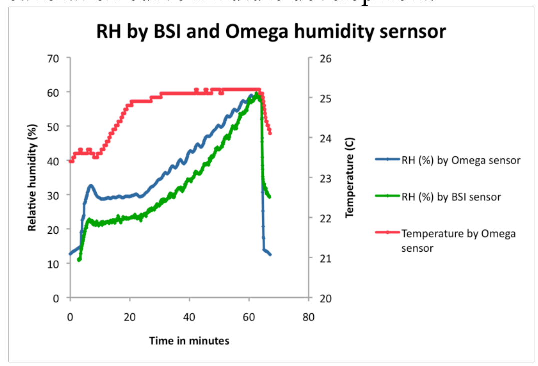
The new humidity sensors placed inside the humidity chamber were characterized with a benchtop Espec BTL-433 humidity chamber. The measured relative humidity (RH) data were compared to those measured by an Omega RHT HX71 series sensor. The RH data of the new humidity sensor were collected by our own data acquisition and display software. The data logging of the Omega RHT sensor was done with the Omega sensor software.

The benchtop series employs a bimodal proportional-integral-derivative (PID) system to control temperature and humidity with a Watlow controller. The bimodal PID system balances temperature and humidity inside the chamber to reproduce the desired conditions. This balance is achieved by alternately controlling the capacity of a cooler and dehumidifier of high heat load, and a heater and humidifying heater of low heat load, in real time. The Watlow instrumentation enables environmental testing under both constant conditions and programmed conditions, referred to as the "constant mode" and the "program mode," respectively. The humidity and the temperature of the inside of the chamber were also measured by an Omega HX71 series relative humidity and temperature sensor with data-logging software. The Omega relative humidity temperature (RHT) sensor has an accuracy of ±3.5% at 23°C in the range of 15-85%.

3.1 Humidity Ramp-up with Constant Temperature

First, the humidity sensor was tested in a constant temperature mode. The ramp profile 1 included the following steps: Step 1: Ramp to a relative humidity of 30% RH at 25°C from ambient in 15 minutes; Step 2: Soak for 5 minutes; Step 3: Ramp to RH of 60% at 25°C from ambient in 35 minutes; Step 4: Soak for 5 minutes; Step 5: Open chamber door.

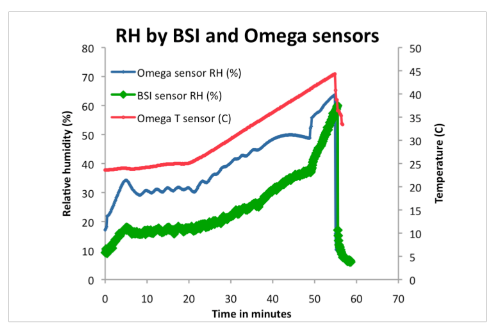
From the figure below, it was discovered that the new humidity sensor gave a nonlinear output at higher RH during constant temperature RH ramping mode. However, this nonlinear output can be corrected by an established calibration curve in future development.



3.2 Humidity Ramp-up with Increasing Temperature

Next, the humidity sensor was tested in an increasing temperature mode. The ramp profile 2 included the following steps: Step 1: Ramp to RH of 30% at 25°C from ambient in 15 minutes; Step 2: Soak for 5 minutes; Step 3: Ramp to RH of 60% at 45°C from 30% RH at 25°C in 35 minutes; Step 4: Soak for 5 minutes; Step 5: Open chamber door.

From the figure below, it was found that the new H-sensor was able to accurately track the sudden change of RH inside the humidity chamber in an increasing temperature ramping mode.

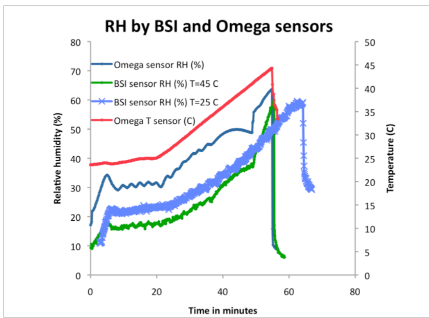


3.3 Decoupled Humidity Sensing with Increasing Temperature

In constant temperature and in increasing temperature ramping cases, the RH was ramped from 30% to 60%. From the RH data shown below, it was discovered that the RH measured by the new humidity sensor is parallel to that of the Omega humidity sensor when the RH is low, even if the temperature is increasing from 25°C

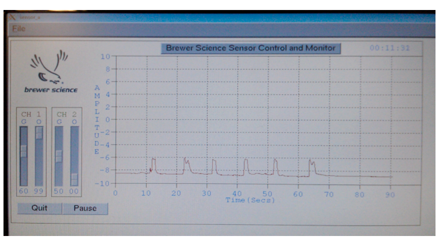
NSTI-Nanotech 2013, www.nsti.org, ISBN 978-1-4822-0584-8 Vol. 2, 2013

to 45°C. When the relative humidity is high, the RH measured by new humidity sensor is not parallel to that of Omega humidity sensor. It was discovered that the nonlinear behavior of the new humidity sensor was due to high RH, not because of high temperature. In other words, we have successfully invented a humidity sensor that can measure humidity independently of temperature.



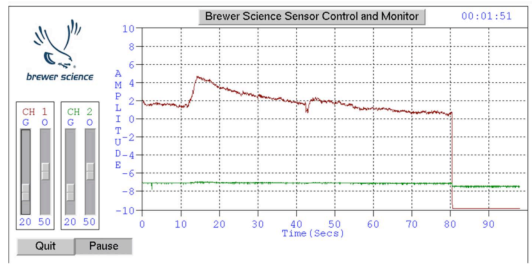
3.4 Humidity Sensing in Human-Breath Sensing Mode

It was discovered that the new humidity sensor could operate in a human-breath sensing mode. A sample screen shot of this mode is shown below.



4. CHARACTERIZATION OF TEMPERATURE SENSOR

To measure temperature using the IDE structure and decouple the humidity signal at the same time, a hermetic seal is needed. A sample screen shot of temperature sensing is shown below.



5. CONCLUSIONS

We successfully invented, fabricated, and characterized a decoupled temperature and humidity sensor made of CNT-based nanomaterials on flexible plastic substrates. The detailed design of sensing elements, electronics hardware, and software are reported. We tested the humidity sensor in constant temperature, increasing temperature mode, and breath-sensing mode. The measured results were compared to those of collected by an Omega RHT sensor. We discovered that our sensor can measure humidity independently of temperature, and it can also detect moisture from human breath. Preliminary results of temperature sensing were presented. In the future, we will explore the possibility of integrating the sensors into our handheld transmitter and receiver developed in-house and commercially available readers.

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