MULTIFUNCTIONAL INTEGRATED SENSOR MONITORING

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ABSTRACT

We deploy multifunctional integrated sensors (MFISES) as a sensing platform in five applications and quantify their performance requirements for: weather stations, indoor climate control, parking monitoring, road activity monitoring, and chemical sensing. MFISES combines temperature, humidity, pressure, air speed, chemical gas, magnetic, and acceleration sensing in an encapsulated fabrication process to yield 2x2 mm sensor die. We compare the measurement resolution, range, and bandwidth of MFISES to application requirements to demonstrate the utility of integrated sensor platforms in a wide range of monitoring situations.

RESULTS AND DISCUSSION

The MFISES design enables a sensing platform engineered to meet target specifications from the literature, datasheets and our own experimental measurements for a number of multi-parameter sensing applications. This work expands an earlier report of the design and fabrication of MFISES [1] and presents MFISES applications in smart environmental and infrastructure monitoring. Integrating the sensor functions onto a single device enables reduction in the size and cost of the sensor components (Fig. 1). The transduction principle, tested range, measured resolution, and bandwidth or time constant data are presented in Table I.

Weather Station

We selected Oregon Scientific's WMR 100 Pro to benchmark weather center performance specifications (Table II) [2]. MFISES exceeds the performance requirements and can provide similar capabilities at a fraction of the size of the sensor system. One advantage of the WMR 100 is that its wind vane anemometer can be self-powered from the input energy of passing air. Whereas, MFISES uses a hot wire anemometer with sensitivity proportional to the temperature difference between the wire and air, which is inherently power dissipative.

Indoor climate control

Three important factors to measure in smart buildings to control the climate system are temperature, humidity, and room occupancy. For temperature and humidity measurements we chose

the Analog Devices TMP36 temperature sensor [3] and the Honeywell HIH-4030 humidity sensor [4] as benchmark devices (Table II). One simple method to determine room occupancy is to detect the opening and closing of a door using a wall mounted accelerometer (Fig. 2a). For this application, we found the average acceleration amplitude for a door closing of $0.12 \text{ g} \pm 0.04 \text{ g}$ with minimum and maximum amplitudes of 0.04 and 0.18 g.

MFISES exceeds the temperature and humidity specifications for indoor climate control and matches the range and resolution of benchmark commercial sensors. Using the y-axis accelerometer, MFISES could detect a minimum amplitude door event with a signal to noise ratio greater than 5. More extensive testing to measure accuracy limited by hysteresis, offset drift, linearity, and long term stability are underway.

TABLE II
Benchmark sensor performance specifications

Function	Range	Resolution	Accuracy
Oregon Scientific WMR 100 Pro weather station			
Temperature	-30 – 60 °C	0.1 °C	1 °C
Humidity	25 – 95 %RH	1 %RH	5 %RH
Pressure	70 – 105 kPa	0.1 kPa	1 kPa
Wind	0 – 56 m/s		3 m/s
TMP35 and HIH-4030			
Temperature	-40 – 125 °C	0.1 °C	2 °C
Humidity	0 – 100 %RH	0.5 %RH	3.5 %RH

Parking monitoring

Programs in San Francisco, CA, USA and Santander, Spain have implemented sensor networks to detect the presence of vehicles in parking spots using magnetometers [5]. Electromagnetic interference from trolley car wires and underground electrical cables has caused reliability issues [6], so additional devices such as proximity sensors or photodetectors are used to verify the magnetometer data. We experimentally measured the magnetic field changes for a mid-size sedan driving over a 3-axis YAS532 magnetometer placed underneath the vehicle (Fig. 2b). The steady state amplitude change of the magnetic field vector was 0.08 G with peaks of 0.4 G when the car

TABLE I
MFISES sensor performance specifications

Function	Sensor	Tested Range	Meas. Resol.	BW, time constant	Power
Temp.	Resonator	-30 – 60 °C	0.02 °C	-	Circuit: 380 mW
	Alum. RTD	-30 – 60 °C	0.03 °C	-	Sensor: 18 µW
Humidity	Polyimide capacitance	30 – 95 %RH	1 %RH	15 sec	Circuit: 8.3 mW
					Sensor: 2 µW
Pressure	Parallel plate capacitance	10 – 101 kPa	0.2 kPa	-	Circuit: 280 mW
Air speed	Hot wire anemometer	10 m/s	0.1 m/s	-	Sensor: 280 mW
Chemical	Carbon monoxide	-	-	5 min	Sensor: 6.5 mW
Magnetic Accel.	Lorentz force y-axis, comb finger cap. z-axis, teeter-totter cap.	-40 – 40 G	0.18 G	-	Sensor: 18 nW
		-1 – 1 g	1.3 mg/rt-Hz	90 Hz	Heater: 0.5 °C/mW
		-1 – 1 g	60 mg/rt-Hz	90 Hz	Sensor: 0.8 mW
					Sensor: 4 µW
					Circuit: 2.5 mW
					Sensor: 4 µW
					Circuit: 2.5 mW

Figure 1: MFISES die is 2x2 mm. Movable sensor elements are encapsulated and environmental sensors are open to ambient conditions.

enters and exits the parking spot. For a single axis, we measured a maximum steady state change of 0.04 G in the axis aligned with the length of the vehicle. The MFISES magnetometer can detect the peaks of a vehicle entering and exiting, but the steady state value is below the resolution limit. Using a three-axis device would raise the minimum detection limit. Researchers have made devices in the same epi-seal fabrication process with the required specifications, but with a larger sensor footprint [11].

Figure 2: (a) Accelerometer data for the closing and opening of three doors shows that a mounted wall accelerometer needs resolution better than 0.12 g to detect door events. (b) Experimental measurements of the change in amplitude of the magnetic field vector (blue line) and the change in the y-axis component (orange line) when a car drives into a parking spot, turns off the engine, turns on the engine, and drives away.

Road activity monitoring

Current road activity monitoring systems count passing vehicles, measure their velocity, or classify them by weight using inductive coils at stop lights, radio frequency transmitter toll tags, traffic cameras, or piezoelectric cables. Here, we are interested in metrics for small-scale sensors placed on the roadside. Kim *et al.* installed a sensor network on structural elements of the Golden Gate Bridge [7] and Whelan *et al.* instrumented an abutment bridge [8]. Maximum measured accelerations were 10 mg sampled at 100 Hz. In our experiments, we placed an STMicro LSM330 accelerometer along an asphalt road and repeatedly drove a mid-size sedan past the sensor at speeds of 20 miles per hour. We were not able to detect the passing of the vehicle above the noise of the measurement. The measured MFISES y-axis accelerometer resolution is 1.3 mg/ $\sqrt{\text{Hz}}$ and theoretical limit is 0.4 mg/ $\sqrt{\text{Hz}}$. With the current measurement setup we cannot measure 10 mg peaks in a 100 Hz bandwidth, but we are investigating how to reduce the parasitic capacitances likely causing the decreased resolution from the theoretical limit.

Chemical sensing

MFISES includes chemical sensing as a multi-parameter monitoring application not only because a chemical sensor system might monitor multiple contaminant gases, but also because many chemical sensors have large cross-sensitivities to temperature, humidity, and other gases [9]. A sensor system needs to measure these cross-dependent parameters to enable compensation in the measurement hardware or software. An example commercial carbon monoxide sensor, the Hanwei MQ-7, has a greater cross-sensitivity to hydrogen gas than to carbon monoxide and temperature and humidity cross-sensitivities of 0.8% full scale output/ $^{\circ}\text{C}$, and 0.4% full scale output/%RH [10].

MFISES demonstrates a platform for detection of chemical gases and compensation of gas sensor cross-sensitivities to temperature and humidity. We measure temperature and humidity

at the level of commercial sensors and conducted a proof-of-concept measurement of carbon monoxide gas with MFISES surface heaters functionalized with tin oxide nanoparticles. Work is underway to assess the detection limit of MFISES.

Figure 3: (a) Microscope image of carbon monoxide sensor with tin oxide nanoparticle sensing film. (b) Infrared image of the heated chemical sensor. (c) Demonstration of detecting carbon monoxide gas. (d) Temperature profile of the infrared image.

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REFERENCES

- [1] C.L. Roozeboom, *et al.*, "Multifunctional integrated sensor in a 2x2 mm epitaxial sealed chip operating in a wireless sensor node," *Proc. of 27th IEEE Intl. Conf. MEMS*, 2014, pp. 773-776.
- [2] Oregon Scientific, "Advanced weather station with wireless sensor set and mounting package," WMR100N datasheet.
- [3] Analog Devices, "Low voltage temperature sensors," TMP36 datasheet, 2010.
- [4] Honeywell, "Humidity sensors," HIH-4030 datasheet, 2008.
- [5] J. Wolff, *et al.*, "Parking monitor system based on magnetic field sensor" *IEEE Intelligent Transportation Systems Conf.*, 2006, pp. 1275-1279, 2006.
- [6] M. Albertson (2011, February). Critical vendor replaced before SFpark launch. [Online]
- [7] S. Kim, *et al.* "Health monitoring of civil infrastructures using wireless sensor networks." *Info. Processing in Sensor Networks*, 2007, 6th Inter. Symp. on, 2007, pp. 254-263.
- [8] M. J. Whelan, *et al.*, "Real-time wireless vibration monitoring for operational modal analysis of an integral abutment highway bridge," *Engineering Structures*, vol. 31, pp. 2224-2235, 2009.
- [9] K.J. Albert, *et al.*. "Cross-reactive chemical sensor arrays." *Chemical Reviews*, vol. 7, pp. 2595-2626, 2000.
- [10] Hanwei Electronics, "MQ-7 gas sensor," MQ-7 datasheet.
- [11] M. Li, *et al.*, "Single-structure 3-axis Lorentz force magnetometer with sub-30 nT/rt-Hz resolution," *Proc. of 27th IEEE Intl. Conf. MEMS*, 2014, pp. 80-83.