SmokeBot

Mobile Robots with Novel Environmental Sensors for Inspection of Disaster Sites with Low Visibility

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Deliverable 2.2

Characterization of response of high-bandwidth (HBW) sensor to target gases and with interferences

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Contents

1. Introduction and purpose of this document

In order to achieve a step change in the field of mobile robot olfaction, work package WP2 in SmokeBot addresses major limitations of state-of-the-art gas sensors. Current metal oxide (MOX) resistive sensors for gas/volatile organic compound (VOC) detection need to be improved upon or replaced in terms of their slow speed of response, power consumption and specificity.

SmokeBot is developing hardware and the corresponding algorithms to detect, identify, quantify, localize and map gases in realistic scenarios. Similarly the response time of polymer based VOC sensors also needed to be shortened; those based upon polymer coatings have low power consumption but need to be improved for selectivity and interference to humidity.

This deliverable describes the specification of sensitive and high-bandwidth (HBW) gas (including VOC) sensors for integration into the SmokeBot technology platform. It describes, in particular, the dynamic response of the sensors to the gases of interest as well as their cross sensitivity to other gases. The two most important sensor types being developed are not only MOX for gases as mentioned above but also acoustic solid mount resonant (SMR) for VOCs. Specifically,

- Fast, low-cost CMOS-based MOX resistive gas sensors
- Ultra-fast, low-power CMOS based polymer SMR VOC sensors.

This deliverable is part of the tasks T2.1 and T2.2, which addresses the specification and design and fabrication of HBW gas sensors. It was compiled by the UWAR after characterization of performances of the fabricated new sensors and discussions of integration issues with other beneficial partners.

2. Design and Implementation of Gas Sensing Unit

Based on previous discussions of the scenarios envisaged for the use of the mobile robot, the gas sensing unit has been designed and its overall functional block diagram is shown in Fig.1 below.

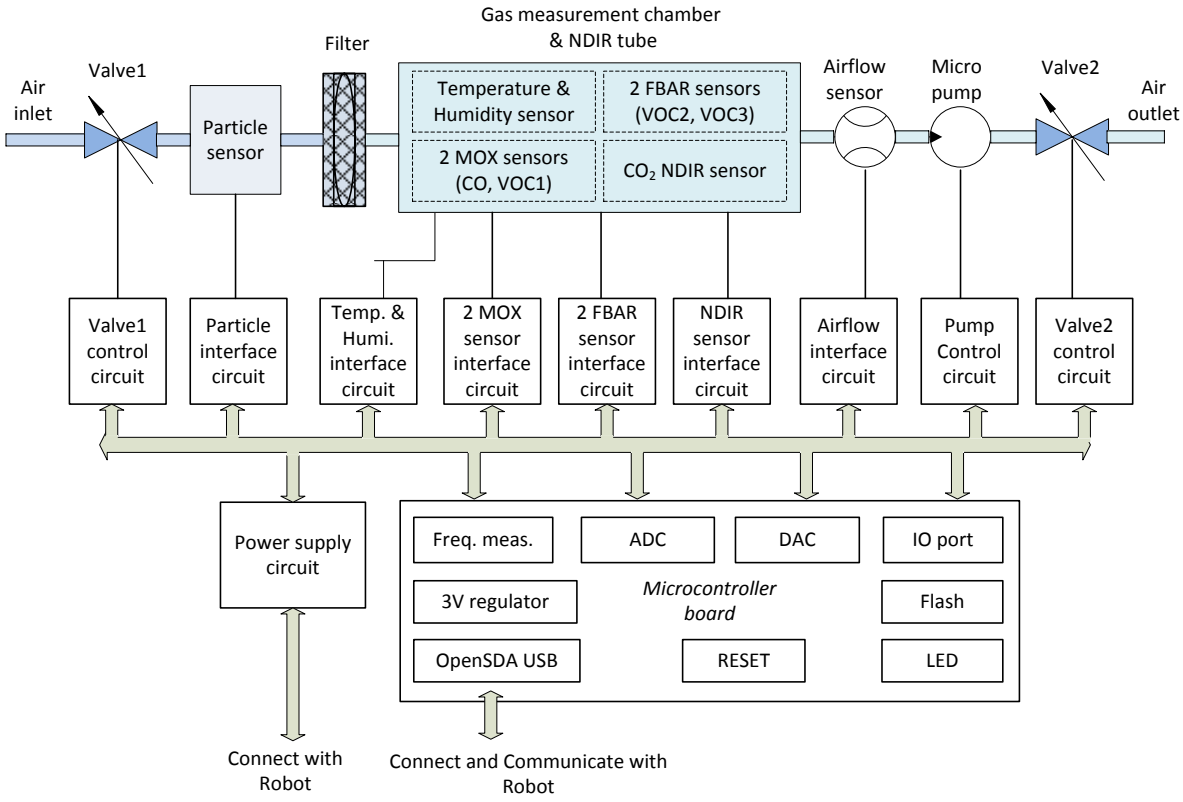


Fig.1: Block diagram of Gas Sensing Unit (GSU) in SmokeBot project

The basic operation of the gas unit is as follows:

- Air is drawn through the air inlet through into internal pipework and the gas measurement chamber by a micro air pump. An airflow rate sensor is also included to monitor the volumetric flow rate, and can used as a reference for closed loop control of the pump speed. This might be necessary to compensate for large changes in ambient air temperature/density.
- Before flowing into the gas measurement chamber, the ambient air is filtered by a physical filter to eliminate the smoke particles. A particle sensor is used to detect the state of the incoming smoke before the filter and can be used to close off the sensors if the particle density is too high and might damage them.
- When the ambient temperature increases to a predefined dangerously high temperature, the electromagnetic valves at the inlet and outlet can be closed and the micro air pump shut off to protect the GSU. This will protect the critical sensors if air temperatures exceed specification.
- In the internal measurement chamber, 6 sensors are housed, which are a temperature and humidity sensor, 2 MOX sensors for detection of CO and NO_2 (or VOC), 2 SMR sensors for detection of two kinds of VOC. An NDIR sensor for detection of high levels of CO_2 is mounted in a following tube. The SMR (FBAR) sensor interface circuit board is designed

separately and easily connected to the main printed circuit board. A new custom application specific integrated circuit (ASIC) has been designed and fabricated to enable a smaller footprint of the sensor in future implementations.

- Temperature and humidity sensors are employed to monitor the state of air drawn in, and also to be used as part of a closed loop control of operating temperature of MOX sensors, as well as the compensation of gas sensor responses.
- To make the sensor more stable and response at higher speed, solidly mounted resonator (SMR) are being used rather than film bulk acoustic wave devices. The operating frequency of the SMR sensors changes when they are exposed to VOCs. Their interface board is discrete in a modular design and future ASICs will be implemented to reduce the frequency from GHz to MHz level suitable to interface directly to the micro-controller I/O port.
- The NDIR sensor needs to be sampled at a higher acquisition rate, averaged and lower bandwidth to reduce thermal noise. Hence increasing the signal-to-noise (S/N) ratio and increase the sensitivity to levels of CO_2 specified in Deliverable 2.1. Moreover the IR emitter is modulated to reduce the effect of baseline drift caused by changes in ambient temperature.
- All circuits of power supply, interface and controlling boards for sensors and actuators have been designed to be compatible with the microcontroller board.
- A UART module of the microcontroller is included to communicate with the robot monitor as requested by Taurob.

The list of sensor specifications is shown in Table 1.

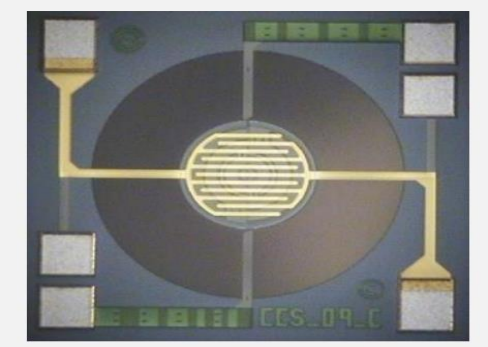
Component	Sensor label	Target gas	Target parameters	Sampling rate	Resolution	output	Sensor sources
CMOS-based metal oxide resistive gas sensor	MOX-CO	CO	10 ppm -1000 ppm resolution 5 ppm	10 Hz	Use 16-bit ADC	Analogue: 0-3V dc	UWAR MOX sensor
	MOX-NO_2	NO_2	PPB level				
CMOS-based polymer film bulk acoustic resonator	SMR-VOC1	Toluene or acetone	PPB level	1 MHz	Use counter	Frequency: bit stream	UWAR SMR sensor
	SMR-VOC2	Formaldehyde or ammonia	PPB level				
optical (NDIR) gas sensor	NDIR-CO_2	CO_2	390ppm – 20% resolution 25ppm	10 Hz	Use 16-bit ADC	Analogue: 0-3V dc	UWAR NDIR sensor
Temperature sensor	TEMP	Temperature	-40°C-125°C	10 Hz	Use 16-bit ADC	Analogue: 0-3V dc	CC2A23
Humidity sensor	HUMI	Humidity	0 to 100% RH (non-condensing)				
Particle sensor	PARTICLE	Particle density		10 Hz	Use 16-bit ADC	Analogue: 0-3V dc	Fairchild H21A3

Table 1: SmokeBot Sensor Specification

3. Characterisation of MOX gas sensors

MOX gas sensors are designed and fabricated for the purpose of detecting CO and NO_2, which are labeled as MOX-CO and MOX-NO_2, respectively. The target is to detect hazardous levels of CO in air from 1,000 ppm down to 10 ppm with a resolution of 5 ppm. MOX-NO_2 sensor is set to test NO_2 at PPB levels in air. MOX-NO_2 can also detect ppm levels of VOCs that react with the chemisorbed oxygen. They will need to be compensated if oxygen levels change and also high temperature and humidity for both MOX gas sensors. Cross sensitivity to other interference gases is needed to be explored.

MOX sensing material shows sensitivity at a high temperature. Therefore, all MOX sensors include a heater to heat up the sensing material, which causes a high power consumption of MOX sensors. To reduce the power consumption and size of MOX sensors, micro-hotplate based MOX sensors have been designed and manufactured. Both MOX sensors in SmokeBot are based on CCS301 high temperature micro-hotplate manufactured based on Micro-electro-mechanical system (MEMS) process. The micro-hotplate is formed from a circular dielectric membrane, supported on a silicon substrate, with a central tungsten heater, produced by a Deep Reactive Ion Etch (DRIE) MEMS process. The inherently low thermal mass allows for rapid heating to high temperature (> 500°C), enabling pulsed mode operation at high frequencies and significantly reducing power consumption. The layout and electrical characteristics of the micro-hotplate is shown in Fig. 2.



Electrical Characteristics

Parameters	Conditions	Typical Value	Units
Operating Temperature		600	°C
Thermal Rise Time (t_{90})		15 ± 5	ms
Thermal Fall Time (t_{10})		30 ± 5	ms
Power Consumption (P_H)[1]	DC @ 600 °C	65 ± 5	mW
Heater Voltage (V_H)[1]		2.2 ± 0.3	V
Heater Current (I_H)[1]		30 ± 4	mA
Heater Resistance (R_0)		80 ± 20	Ω
Ambient Resistance (R)		40 ± 10	Ω
Sensing Area		0.05	mm^2

Figure 2: Layout and electrical characteristics of micro-hotplate

3.1 MOX-NO_2 gas sensor

The WO_3 materials have been tested and found to be a suitable material for NO_2 detection. Three kinds of WO_3 sensing film were fabricated and deposited onto the micro-hotplates, which are labeled as New Met (CCS), New Met (UoW) and Fluka. Their dynamic responses to NO_2 in the concentration range of 10 ppb to 250 ppb in dry air and wet air are explored as well as cross sensitivity to other interference gases.

3.1.1 MOX-NO_2 sensor based on New Met (CCS)

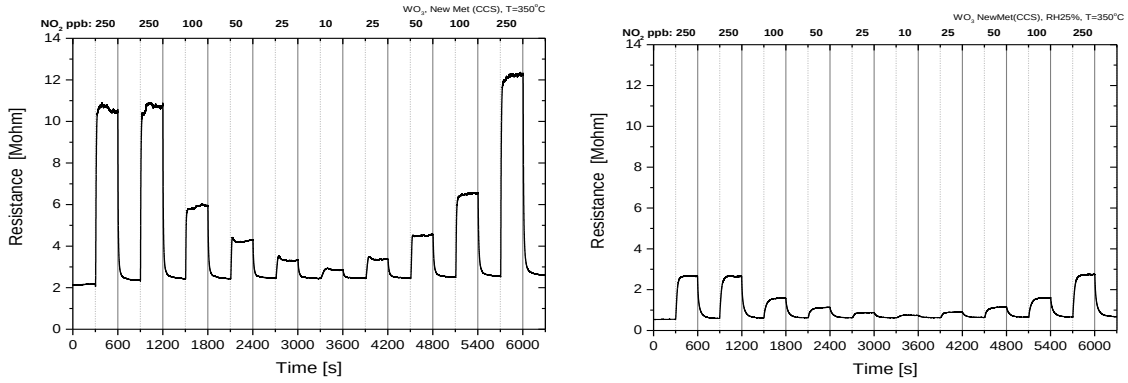
New Met (CCS) labeled WO_3 powders are provided by CCS and has been doped by rare metals. The material is deposited to the micro-hotplate and annealed at 350°C. The MOX-NO_2 sensor is operated at 350°C, which shows better sensitivity to NO_2. The sensors are measured by a test rig. The airflow is controlled at 0.5 standard liter per minute (slpm). All the experiments were operated at room temperature. Table 2 shows the explored gases in the experiments. The cross sensitivity of MOX-NO_2 sensor to acetone, CO, H_2S, H_2 and CH_4 at different concentration ranges are measured as well as the interference of humidity. The sensors are measured in air 5 min, in detected gas at set concentration 5

min, then in air 5 min, and so on. The dynamic variations of sensor resistance (MΩ) over time (second, s) are shown in the following figures.

	Gas	Measured concentration range	Humidity	Data plot:
Target	NO_2	10 ppb – 250 ppb	0	Fig.3(a)
			25%RH	Fig.3(b)
Interferences	Acetone	100 ppm – 300 ppm	0	Fig.4(a)
			25%RH	Fig.4(b)
	CO	1 ppm – 50 ppm	0	Fig.5(a)
			25%RH	Fig.5(b)
	H_2S	100 ppb – 5 ppm	0	Fig.6(a,b)
			25%RH	Fig.6(c,d)
	H_2	2% - 500 ppm	0	Fig.7(a)
	CH_4	500 ppm-1.5%	25%RH	Fig.7(b)

Table 2: Explored gases and VOCs

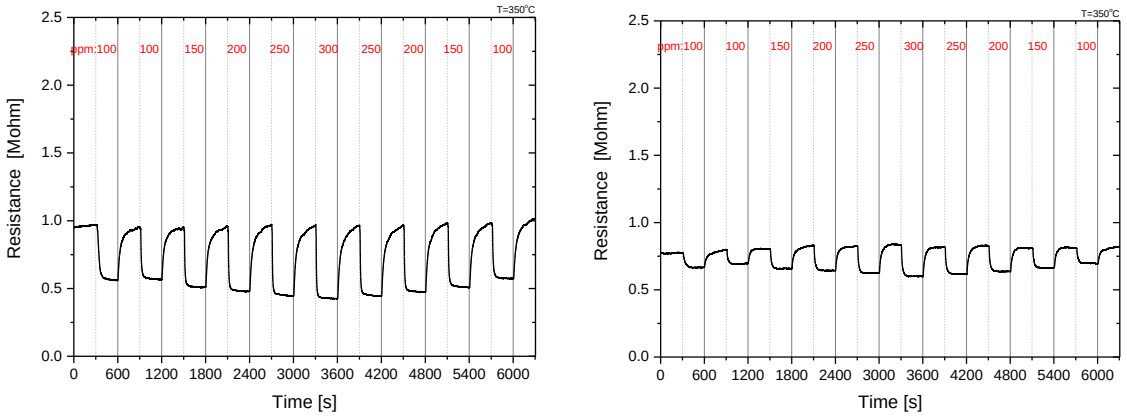
MOX-NO_2 sensor is exposed to 250 ppb, 250 ppb, 100 ppb, 50 ppb, 25 ppb, 10 ppb, 25 ppb, 50 ppb, 100 ppb and 150 ppb NO_2 gas in dry zero air (note that purified atmospheric air to contain less than 0.1ppm total hydrocarbons.) and wet zero air of 25% relative humidity (RH). Results are shown in Fig.3. It can be seen that the MOX-NO_2 sensor shows response to 10 ppb of NO_2, and humidity does affect the response of sensors.



(a) (b)

Fig.3: Dynamic response of NewMet (CCS) MOX sensor to NO_2 in dry (a) and RH 25% (b) zero air.

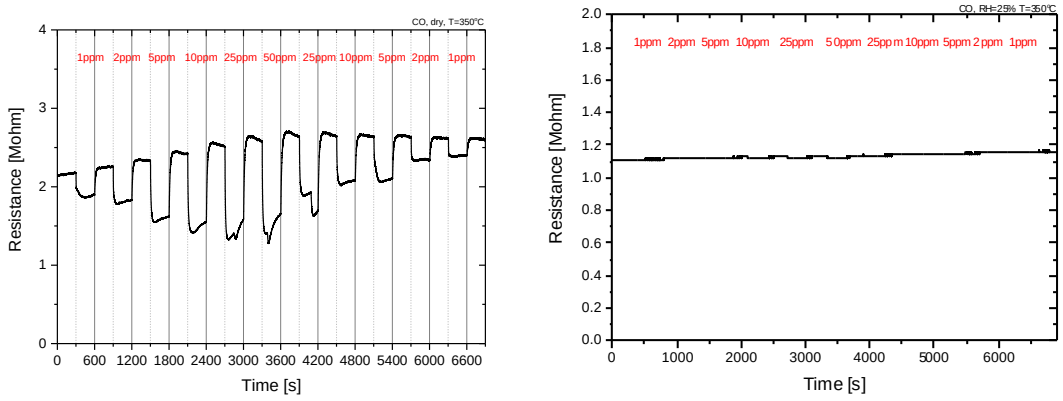
To see the cross-sensitivity of MOX-NO_2 sensor, it is exposed to 100 ppm, 100 ppm, 150 ppm, 200 ppm, 250 ppm, 300 ppm, 250 ppm, 200 ppm, 150 ppm and 100 ppm of acetone in dry zero air and wet zero air of 25% relative humidity. Results are shown in Fig.4. It can be seen that the MOX-NO_2 sensor shows sensitivity to acetone, and humidity does affect the response of sensors. Therefore, signal processing to reduce the cross-sensitivity is necessary. Improving the sensing material is another approach to improve selectivity of sensors to NO_2.



(a) (b)

Fig.4: Dynamic response of NewMet (CCS) MOX sensor to acetone in dry (a) and RH 25% (b) zero air.

To see the sensitivity of MOX-NO_2 sensor to CO, it is exposed to 1 ppm, 2 ppm, 5 ppm, 10 ppm, 25 ppm, 50 ppm, 25 ppm, 10 ppm, 5 ppm, 2 ppm and 1 ppm of CO in dry zero air and wet zero air of 25% RH. Results are shown in Fig.5. It can be seen that the MOX-NO_2 sensor shows sensitivity to COin dry air, but almost no response to CO in 25%RH wet air.



(a) (b)

Fig.5: Dynamic response of NewMet (CCS) MOX sensor to CO in dry (a) and RH 25% (b) zero air.

H_2S is also an interested gas to be measured. To see the sensitivity of MOX-NO_2 sensor to H_2S, it is exposed to several concentrations of H_2S. Results are shown in Fig.6. Fig.6 (a) and (c) shows sensor response to 5 ppm, 5 ppm, 4 ppm, 3 ppm, 2 ppm, 1 ppm, 2 ppm, 3 ppm, 4 ppm, 5 ppm of H_2S in dry zero air and wet zero air of 25% RH, relatively. It can be seen that the MOX-NO_2 sensor shows sensitivity to H_2S in dry air, but smaller response to H_2S in 25%RH wet air. Fig.6 (b) and (d) shows sensor response to 1 ppm, 1 ppm, 0.5 ppm, 0.25 ppm, 0.1 ppm, 0.1 ppm, 0.25 ppm, 0.5 ppm, 1 ppm of H_2S in dry zero air and wet zero air of 25% RH, relatively. Results show that MOX-NO_2 sensor could response to 0.1 ppm H_2S and smaller response when humidity is 25%RH.

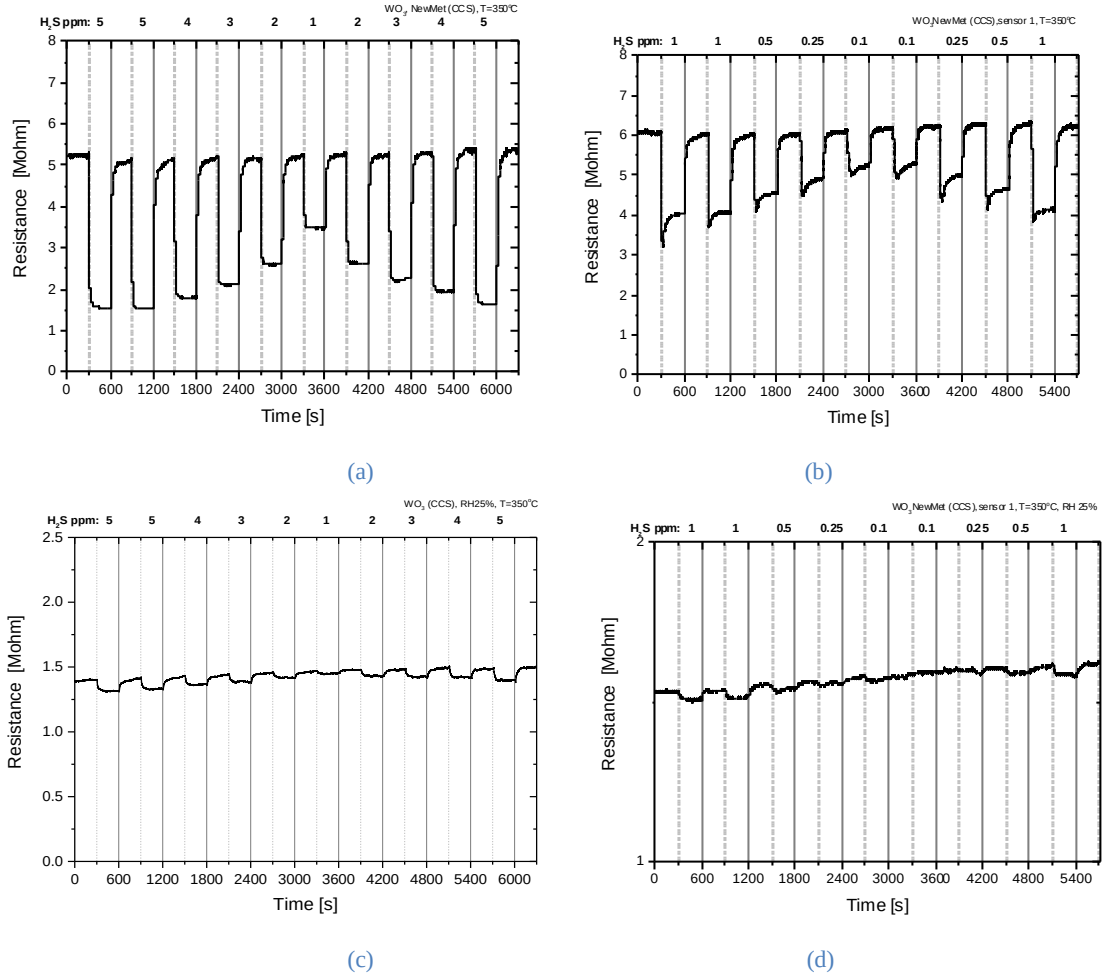


Fig.6: Dynamic response of NewMet (CCS) MOX sensorstoH_2S in dry (a,b) and RH 25% (c,d) zero air.

Response of MOX-NO_2 sensors based on New Met (CCS) to 2%, 1.5%, 1%, 0.5%, 0.25%, 0.1%, 0.05%, 0.05%, 0.1%, 0.25%, 0.5%, 1%, 1.5%, 2% H_2 in dry zero air and wet air of 25%RH are shown in Fig.7. The sensitivity is relatively smaller than to other investigated gases. And there is almost no response when in wet air of 25%RH.

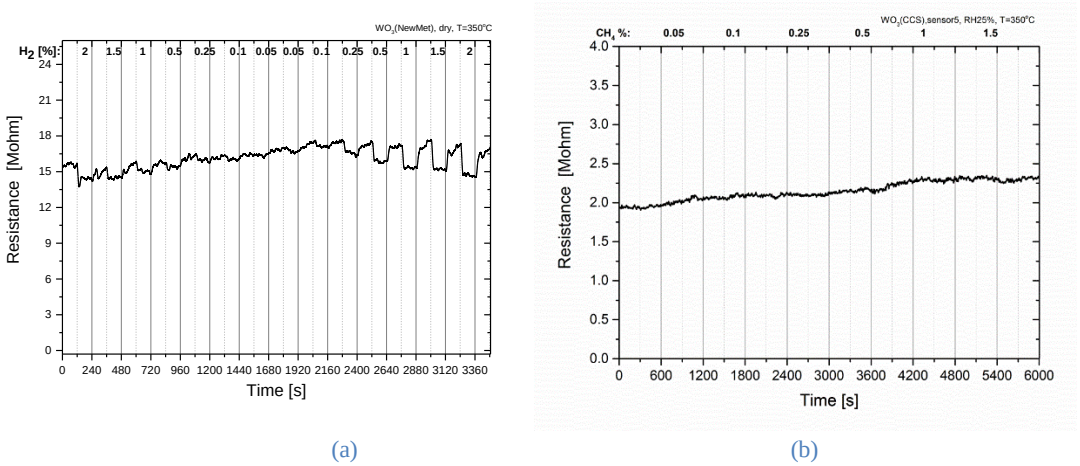


Fig.7: Dynamic response of NewMet (CCS) MOX sensorstoH_2in dry (a) and CH_4in wet (RH25%) zero air.

In the SmokeBot project, CO and NO_2 are the two target gases specified in Deliverable 2.1. Therefore, the sensitivity of the sensor to these two gases are critical. To compare the sensitivity of the sensor to these two gases, the normalised resistance (R_{gas}/R_{air}) is calculated and shown in Fig. 8. It can be seen that there is high selectivity of NO_2 of this kind of sensor.

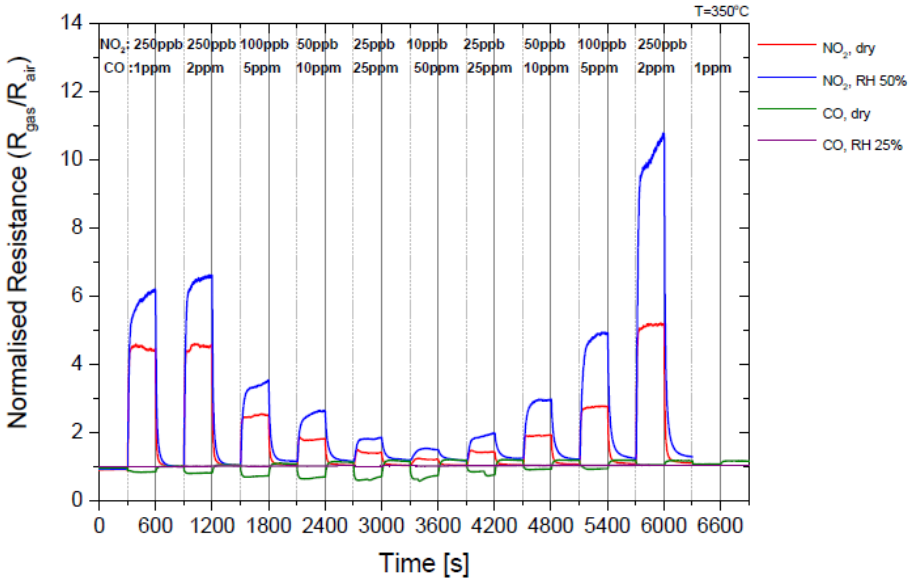


Fig.8: Response to a set of PPB level pulses of NO_2 with MOX-NO_2 gas sensor.

MOX-NO_2 sensor based on New Met (CCS) shows good sensitivity to NO_2 and good selectivity to CO. It has been used in the project. And it shows sensitivity to acetone, H_2S as well. Following signal processing to reduce the cross sensitivity is necessary.

Further improvement of MOX-NO_2 sensing materials on reducing cross sensitivity to other gases and humidity is being considered. Other kinds of doping with rare metals are being tried and studied.

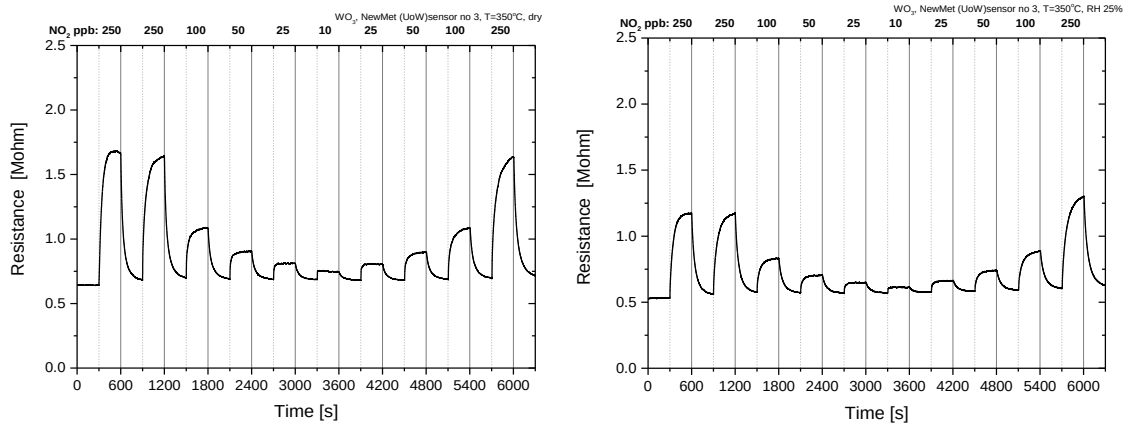
3.1.2 MOX-NO_2sensor based on New Met (UoW)

Another WO_3 sensing material based on New Met is fabricated and the sensor response to NO_2 and H_2S was explored. Concentration settings are shown in Table 3.

	gas	Measured concentration range	humidity	data
Target	NO_2	10 ppb – 250 ppb	0	Fig.8(a)
			25%RH	Fig.8(b)
Interferences	H_2S	100 ppb – 5 ppm	0	Fig.9(a,c)
			25%RH	Fig.9(b,d)

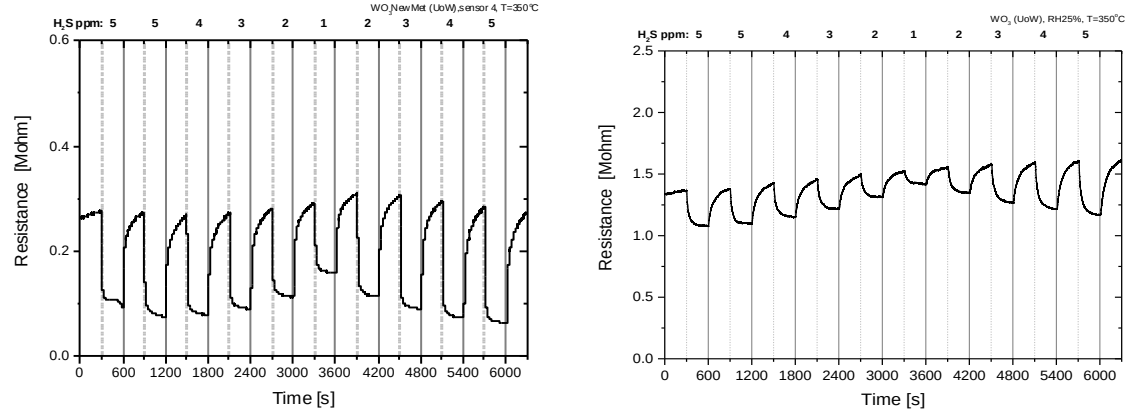
Table 3 Explored gases

Dynamic responses to NO_2 in dry air and wet air are shown in Fig.8. It can be seen that the humidity influence is smaller than sensor based on New Met (CCS) shown in Fig.3. However, this sensor has longer response time than previous one (which is preferred by SmokeBot). Sensitivity to H_2S is studied, results are shown in Fig.9, which is similar with the New Met (CCS) based NO_2 sensor. Hence, there is no necessity to study the cross-sensitivity of the sensor to other gases in this project.

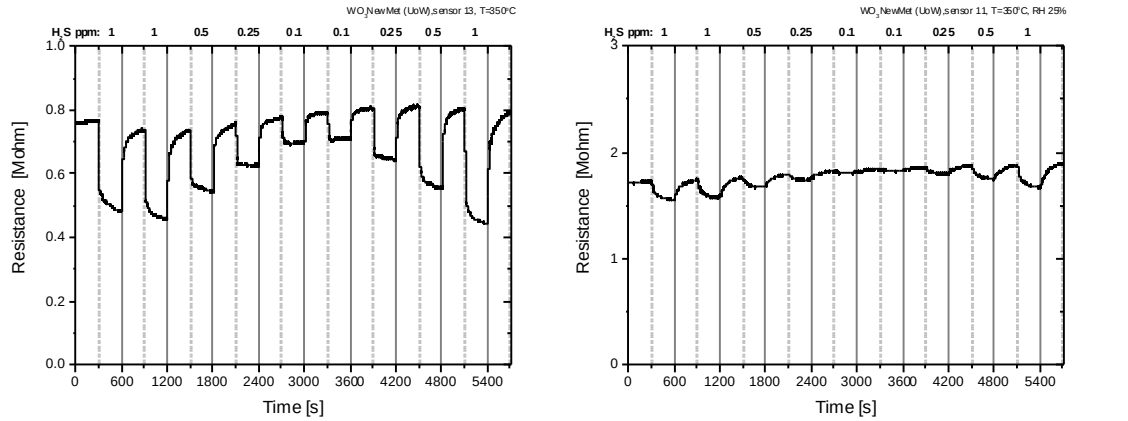


(a) (b)

Fig.8: Dynamic response of NewMet (UoW) MOX sensor to NO_2 in dry (a) and RH 25% (b) zero air.



(a) (b)



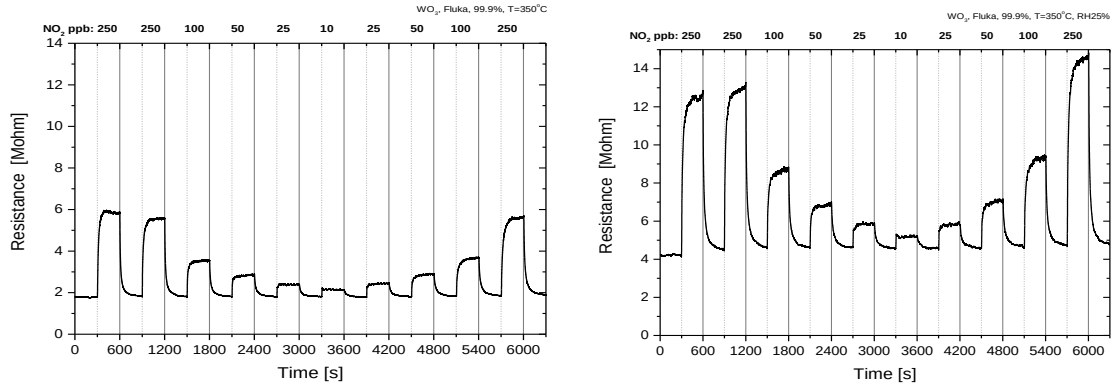
(c) (d)

Fig.9: Dynamic responseof NewMet(UoW) MOX sensor to H_2S in dry (a,c) and RH 25% (b,d) zero air.

3.1.3MOX-NO_2 sensor based on Fluka

To further improve the selectivity, a WO_3 material based on Fluka (99.9%) was fabricated and the sensor response to NO_2 are explored, shown in Fig.10. Test is performed in dry (a) and 25%RH (b)

zero air, total flow 1.2 slpm, T=350°C. It can be seen that in wet air, the response to NO_2 is increased much more than previous two kinds of NO_2 sensors. Therefore, no cross-sensitivities to other gases are investigated and the sensor is not selected in SmokeBot project.



(a) (b)

Fig.10: Dynamic response of FlukaMOX sensor to NO_2 in dry (a) and RH 25% (b) zero air.

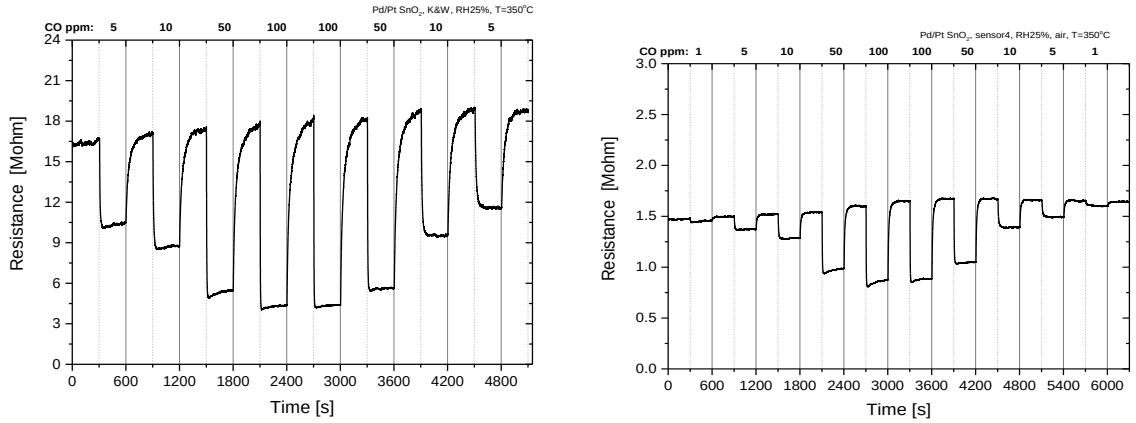
3.2 MOX-CO gas sensor

To detect CO in the environment, the Pd/Pt doped SnO_2 material is studied and fabricated combining with the microhotplate. Sensors are measured by an automated test rig. Sensors are controlled working at 350°C temperature, and are exposed to target CO gas pulses of 5 min. CO concentration is stepped in the range of 5-100 ppm, which are 5 ppm, 10 ppm, 50 ppm and 100 ppm. Results are shown in Fig. 11(a). It could be seen that the response of sensors are stepped changing and returning to a baseline of zero air. Test was performed in RH 25% zero air at room temperature. Fig.11(b) shows another gas sensor responses to varying CO concentration (1-100ppm) at same humidity and temperature. Response to 1ppm can be seen. Comparing (a) and (b), the baseline resistance of two sensors are different, which is a common problem in MOX sensors. Normalization is needed for further processing.

The sensor response to NO_2, H_2, and CH_4 are measured. Concentration ranges are shown in Table 4. Results are shown in Fig. 12. It can be seen that MOX-CO sensor shows response to NO_2 and CH_4, and high response to H_2. Hence signal processing is necessary to reduce the cross sensitivity.

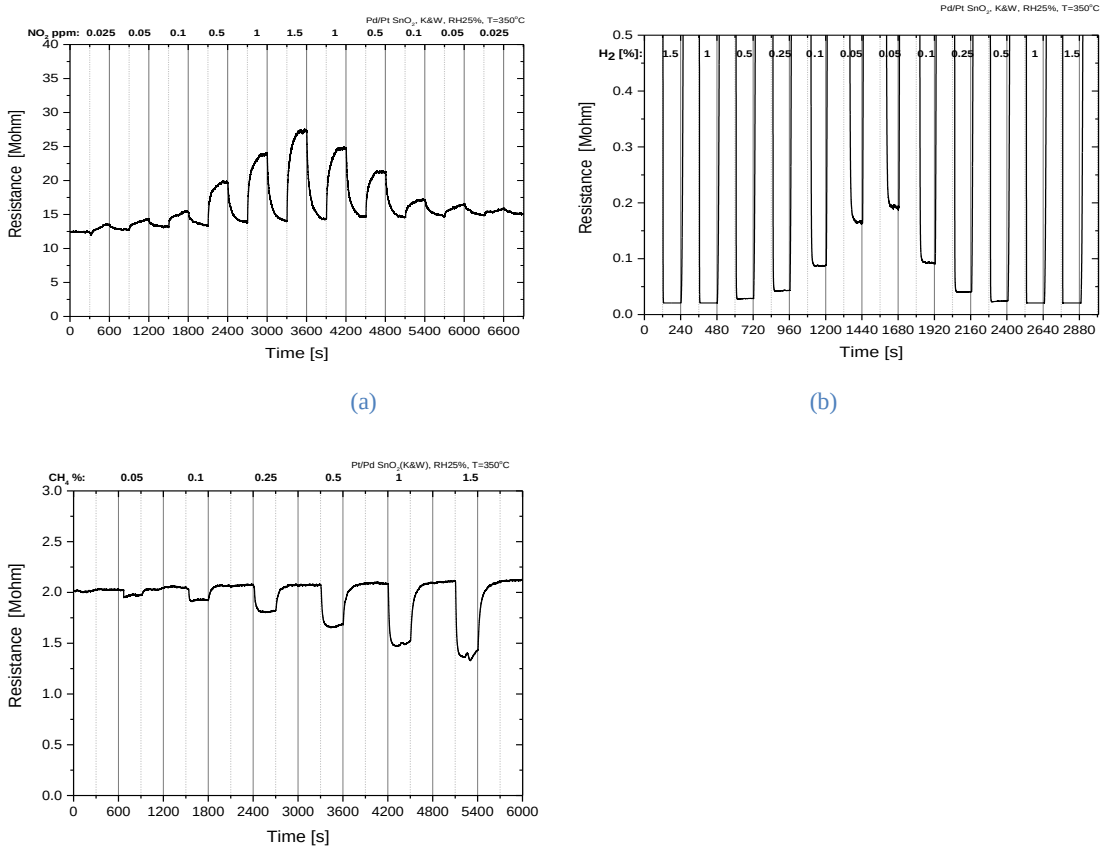
	Gas	Measured concentration range	Humidity	Data
Target	CO	5ppm – 100ppm	25%RH	Fig.11(a)
		1ppm – 100ppm	25%RH	Fig.11(b)
interferences	NO_2	25ppb-1.5ppm	25%RH	Fig.12(a)
	H_2	500ppm-1.5%	25%RH	Fig.12(b)
	CH_4	500ppm-1.5%	25%RH	Fig.12(c)

Table 4: Explored gases



(a) (b)

Fig.11: Dynamic response of Pd/Pt SnO_2MOX sensor to CO in wet (RH25%) air (a) sensor1 (b) sensor4



(a) (b)

(c)

Fig.12: Dynamic response of MOX-CO sensor to interference gases (a) response to NO_2in air, 25ppb-1.5ppm with humidity of RH 25% (b) response to H_2 in air, 500ppm-1.5%, total flow 0.5 slpm, 2 min. steps, RH 25%, T=350°C (c) response to CH_4 in air, 500ppm-1.5%, total flow 0.5 slpm, 10 min. off/ 5min. on steps, RH 25%, T=350°C

The two kinds of MOX gas sensors have been tested by UWAR using a lab-based automated gas test station. The MOX-CO sensor uses a thick film of tin dioxide with metal additives (Pd and Pt) to

improve its stability in humid environments. The response to a set of PPM level pulses of CO is shown in Fig. 11. The sensitivity to PPM levels of CO is excellent and the response time is about 20 s. There is a small baseline drift but this is low compared with the large response. The response is sensitive to the humidity and will reduce by about 20% from dry to wet conditions. Hence compensation needed as stated above for precise measurements. The response to a set of PPB level pulses of NO_2 is shown in Fig.3.The sensitivity to PPB levels of NO_2 is outstanding and can be measured easily. In this case the film resistance increases rather than decreases with higher concentrations. The target gas concentration range of MOX sensors has been achieved. There is almost no cross-sensitivity to CO as can be seen in Fig. 8, but there is again some sensitivity to humidity that needs to be compensated for accurate measurements.

Fig.13 shows the dynamic response of MOX-CO sensor to 5 ppm of CO in wet air of 25%RH. It can be seen that the response time is about 20 s. There is a similar response time of some 20 s for MOX-NO_2 sensors and a slightly longer recovery time for both MOX sensors, which is about 2-3 times of response time. The response time parameter is a bit longer than the target specification, but it could be improved by operating the sensors at higher temperature and by using dynamic features combining with the following signal processing algorithms.

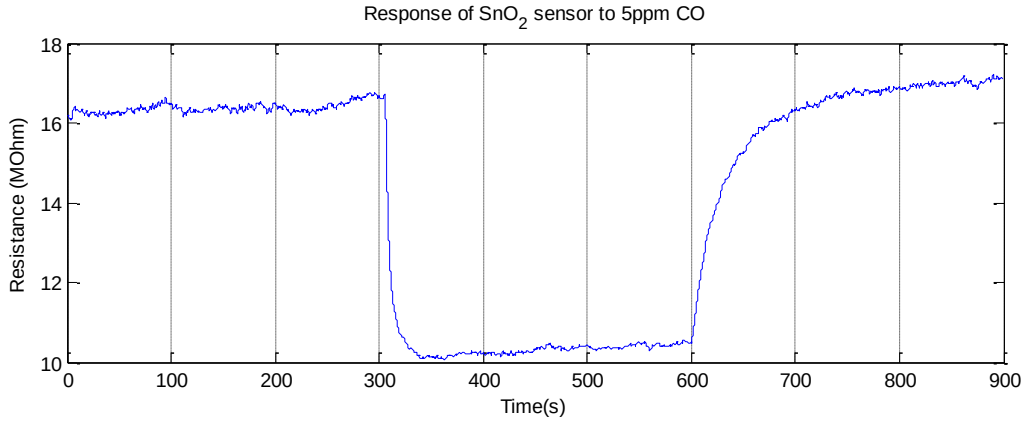


Fig.13: Dynamic response of MOX-CO sensor to 5 ppm CO in wet air of RH 25%, T=350°C.

4. Characterisation of NDIR-CO_2 gas sensor

A Non-Dispersive Infrared (NDIR) sensor unit has been developed to detect high levels of CO_2 in air.

Fig.14 shows the response of NDIR sensor to repeated pulses of CO_2 at levels 0.5%, 1%, 2%, 3%, 4% and 5% in dry zero air at room temperature. It can be seen that sensitivity is quite large. The response time is about 1seconds, which shows fast response.

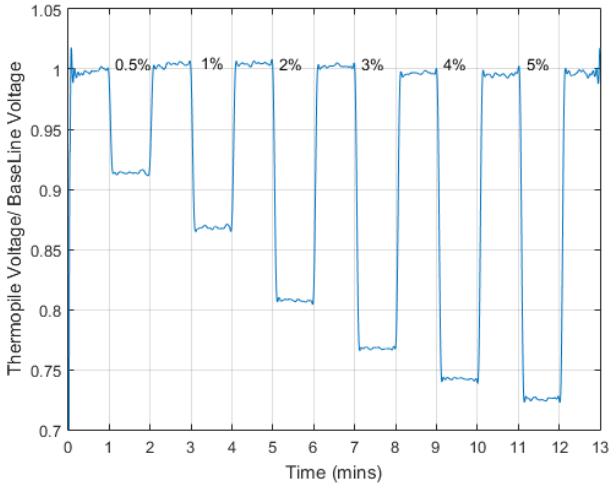


Fig.14: Response of NDIR sensor to increasing pulses of CO_2

Fig.15 shows the response of NDIR sensor to repeated pulses of CO_2 at levels 0.5%, 1%, 2%, 3% and 4%. At the same time the amount of oxygen is being decreased from ambient 20% to 16%. It can be seen that the output of the NDIR sensor is independent of the oxygen level in the room. This is excellent news for sensing CO_2 levels in a room with a fire because the oxygen level in the room could be much lower than 20%.The response time of the NDIR is a few seconds because of signal filtering and sample averaging to reduce the noise. Changing the filter in the NDIR to methane wavelengths (3.3 microns) should yield similar results for 4% LEL for combustion. The NDIR sensor does show sensitivity to ambient temperature and humidity (and particle density). The sensors will be thoroughly tested to other interference gases and algorithms will be developed that reduce the cross-sensitivity between gases and VOCs (where it exists) and also the effect of changes in air temperature, humidity and particle density in future researches.

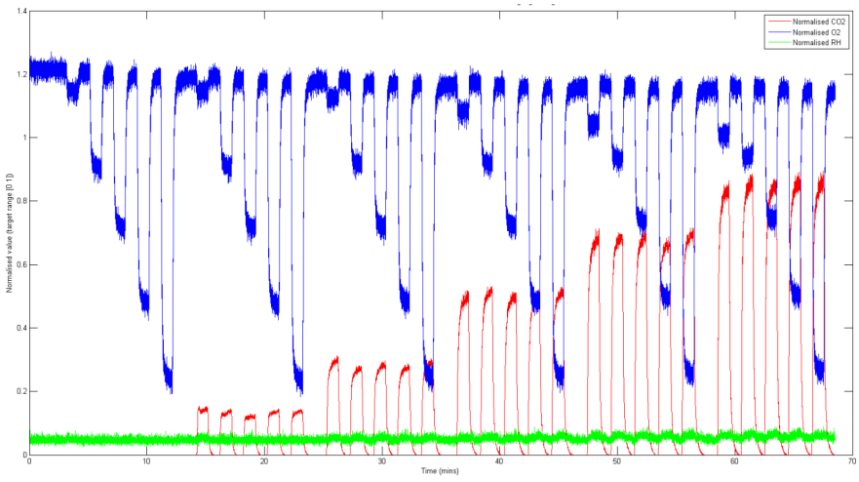


Figure 15: Response of NDIR sensor to increasing pulses of CO_2 (at different oxygen levels)

5. Characterisation of SMR-VOC gas sensors

Key to the development of ultra-fast, low-power CMOS based polymer SMR VOC sensors are thinner polymer films (down to 100 nm) to get shorter response times (down to 10 ms instead of several seconds). A higher operating frequency is used to improve upon the sensitivity and PPB levels of

VOC detection should be possible. Two SMR sensors will be incorporated and each with a reference SMR to compensate for drift from changing ambient conditions. The use of two sensor will help separate both hydrophobic and hydrophilic solvents.

New, ultra-fast, low-power, high frequency (970 MHz) CMOS-based film bulk acoustic resonator (SMR) sensors have been developed for VOC monitoring and are currently under test.

The new SMR sensors will be coated with specific polymers tailored to target the VOCs of interest within this project, for example hazardous organic solvents like formaldehyde and acetone. Our previous research on acoustic sensors operating at much lower frequencies of 260 MHz has demonstrated sensitivity to VOCs at the PPM levels. This work was on surface acoustic wave resonator (SAWR) sensors and has shown that VOCs can be detected at the ppm level using thin polymer coatings. Fig.16 shows that alcohols and esters can be detected using these devices. However, there is cross-sensitivities and so signal processing will be required to recognize specific VOCs and remove interferences from other VOCs. Increased operating frequency (from 260 MHz to about 1 GHz) should result in increased sensitivity to target VOCs: toluene, acetone, formaldehyde and ammonia.

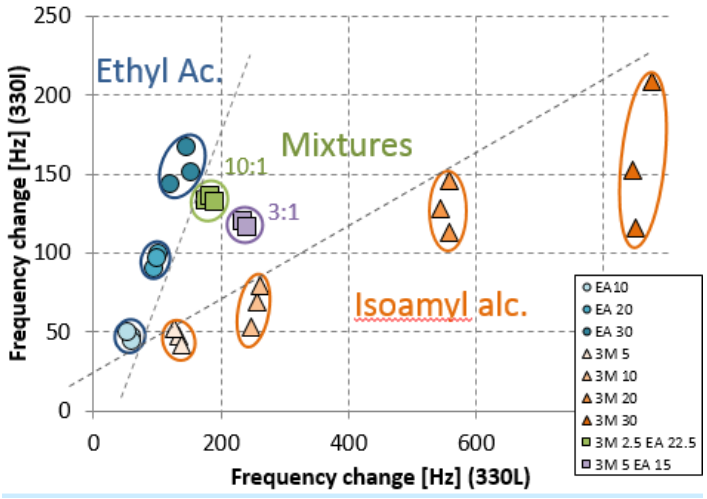


Fig.16: Response of two polymer coated SMR sensors to two VOCs, where EA denotes the Ethyl Acetate, 3M denotes the 3-methyl-1-butanol, which is a kind of isoamyl alcohol. EA 10 means 10ppm EA, 3M 5 means 5ppm of 3M, and so on.

Initial characterization of SMR sensors is currently underway. Thinner coatings of the polymers should also lead to faster responses and so higher bandwidths. Figure 17 shows a graph of the SMR sensor response to 300ppm toluene. This is about 15 kHz frequency shift for 300ppm of toluene but the signal is very noisy. Further results on this kind of sensor will be submitted in the following report.

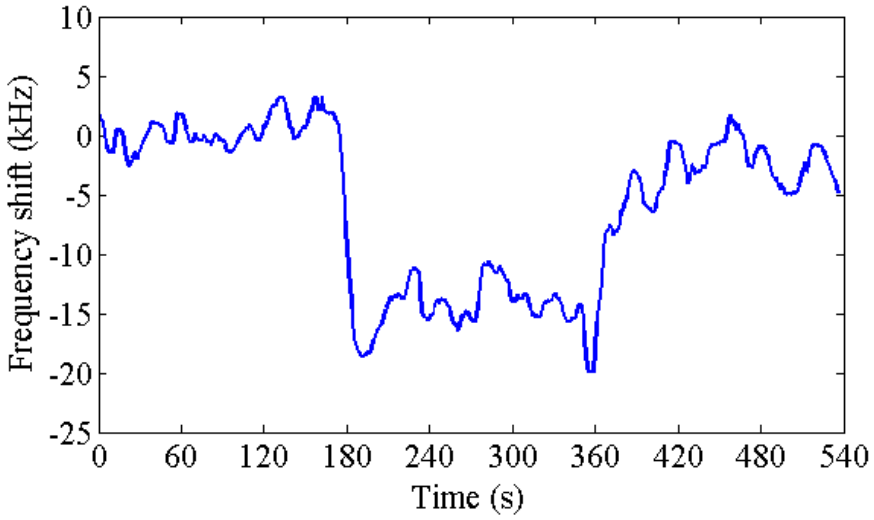


Fig.17: Response of SMR sensor to 300ppm toluene

6. Conclusions and link to Future Development and Deliverables

Characterisation of individual sensors is of great importance for further applications in SmokeBot and the development of gas sensing unit. The performances of MOX sensors, NDIR sensors and SMR sensors are described in this deliverable. Following the individual characterization the sensors have been deployed in the development of the gas sensing unit.

In addition to the specification of gas/VOC sensors, during the development process care was taken that the gas sensing unit can easily be integrated into the SmokeBot demonstrator platform. A local micro-controller board that can monitor the sensor outputs and perform other peripheral functions as shown in Figure 1was also included within the gas sensing unit.

The responses of the HBW gas sensors to target gases and in the presence of interferences will be used as further references in development signal processing methods. Also as part of Task T2.2, the HBW MOX and SMR sensors will be validated in a wind-tunnel using tailor-made signal processing algorithms. The results will be reported in Deliverable D2.3, which is due in M18. Models can be hosted remotely to save power and resources. However the use of a micro-controller will allow local feature extraction if required.

The response times of the different sensors vary from ~ ms for the VOC SMR sensors to ~1 s for the NDIR gas sensor and ~10 s for the MOX sensors. These speeds are more than sufficient for the implementation on the Taurob robot. In addition the time taken for the air sample to reach the sensors in the chamber can also be of the order of seconds for the flow-rates used here.

As a result of Task T2.1 a gas sensor unit has been produced, comprising interface circuitry, the fabricated HBW gas sensors, as well as temperature, air flow and humidity sensors and an airflow pump. The development and characterization of the complete unit will be reported in Deliverable D2.4 in M21. From then on, the novel gas sensing unit will be used in the development of gas detection and identification algorithms (Task T2.3), gas distribution and airflow mapping (Task T2.4) and gas source

localization (Task T2.5) approaches. In meantime, the developments in T2.3, T2.4 and T2.5 are based on commercially available state-of-the-art sensors.