SmokeBot

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

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Deliverable 2.4

Fabricated sensor and interface circuitry for integration of high-bandwidth chemical sensor on robot platform

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Main Authors:

Prof. Julian Gardner (UWAR)
Dr. Marina Cole (UWAR)
Dr. Guangfen Wei (UWAR)

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0.3: revised version, various, 11 July, 2016

Contents

1. Introduction and purpose of this document

Work package (WP2) in the SmokeBot project studies the high-bandwidth (HBW) gas sensors, their corresponding hardware and algorithms to detect, identify, quantify, localize and map gases in the different application scenarios.

To ameliorate the major limitations of state-of-the-art solid-state gas sensors, SmokeBot is developing fast, low-cost CMOS based metal oxide (MOX) resistive gas sensors (and fast optical Non-Dispersive Infra-Red (NDIR)), and ultra-fast, low-power CMOS based polymer Solidly Mounted Resonator (SMR) Volatile Organic Compound (VOC) sensors for mobile robotic applications[1]. Two tasks are addressing these challenges. Task T2.1 addresses the specification, design and production of sensitive and fast HBW gas sensors. Task T2.2 validates the HBW MOX and SMR sensors in a wind tunnel using tailor-made signal processing algorithms. We will also test new optical sensors at the same time for CO_2 detection.

To handle realistic scenarios, existing algorithms to detect, identify, quantify, localise and map gases need to be improved. Three tasks are addressing the challenges. Task T2.3 focuses on the gas detection and identification algorithms; Task T2.4 puts together all the information about gases in map form. Task T2.5 localizes the gas source based on the maps.

Two deliverables have already been submitted:

- Deliverable D2.1 which describes the technical specification of HBW chemical sensors.

- Deliverable 2.2 describing the characterization HBW sensors to target gases without and with interferences.

Based on the manufactured sensors and characterization results, the Gas Sensing Unit (GSU) has been designed and fabricated for the purpose of integration with the moving robot. This deliverable addresses the design of the GSU housing fabricated sensors and interface circuitry for integration of HBW gas sensors on robot platform. This deliverable is part of Task T2.1 and T2.2. It was compiled by UWAR after building up the module and initial integration with the mobile robot.

[1]Note that FBAR was written in the proposal. However, to make the sensor more stable and response at higher speed, Solidly Mounted Resonator - SMR sensors are developed which are also acoustic resonant devices.

2. Design and Implementation of Gas Sensing Unit

Based on the discussion on the scenarios envisaged for the mobile robot, the gas sensing unit has been designed and its block diagram is shown in Fig.1 below. The unit houses more sensors and features than originally proposed in order to have wider application and enhanced capability in harsh environments.

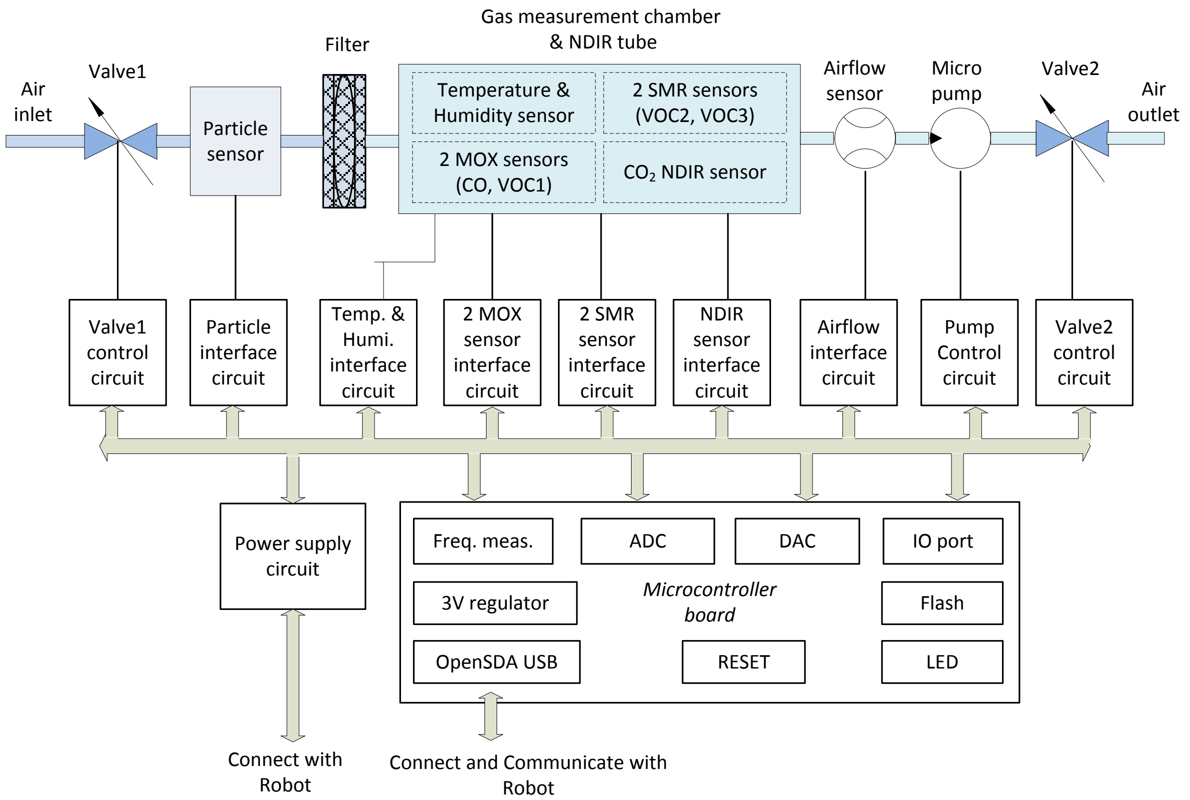


Fig.1: Block diagram of Gas Sensing Unit (GSU) for SmokeBot project

The operating procedure is as follows:

- The air is drawn into the internal pipework and gas measurement chamber by a micro air pump. An airflow rate sensor is employed to monitor the volumetric flow rate, which is used as a reference sensor to control the pump speed. This could be needed when the air temperature and density vary considerably – closed loop control would improve measurement accuracy.
- 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 (set by particle detector threshold) and might damage them.
- When the ambient temperature increases to a dangerously high temperature (limit set by operator), the electromagnetic valves at the inlet and outlet are closed and the micro air pump is shut off to protect the GSU. This will protect the sensors if air temperatures exceed specification.

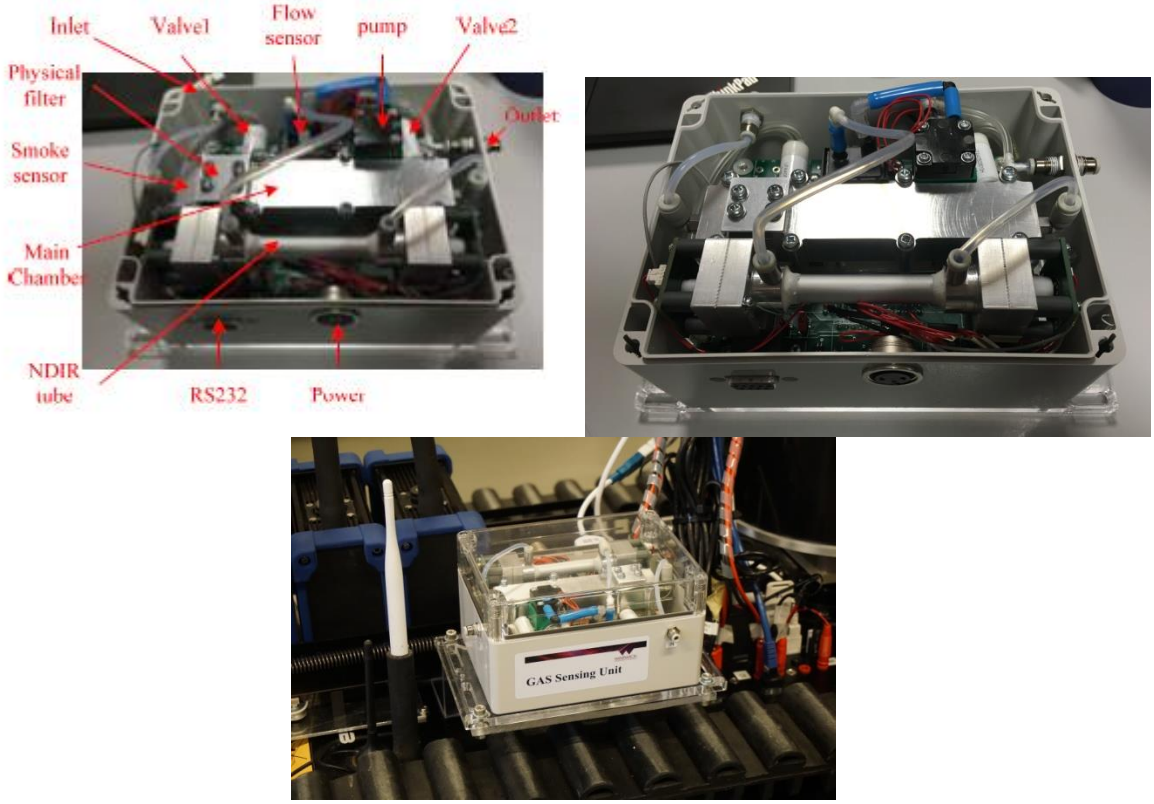
- Inside the internal measurement chamber, there are 6 sensors: temperature and humidity sensor, 2 MOX sensors for detection of CO and NO_2, 2 SMR sensors for detection of two kinds of VOCs. Custom designed NDIR optical sensors for detection of high levels of CO_2 are mounted in a separate tube. The SMR sensor interface circuit board is designed separately and easily connected to the main board. Custom application specific integrated circuit (ASIC) has been designed and fabricated to minimize the size of the board.
- Temperature and humidity sensors are employed to monitor the 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.
- The response of SMR sensors is the change in resonant frequency when the polymer coating absorbs the VOC. In the first embodiment the interface board comprises a first generation ASIC chip and discrete components and reduces the frequency from GHz to <1MHz handled by the simple micro-controller. A second ASIC is under development for a later version that will be much smaller.
- The NDIR sensor needs to be sampled at a high acquisition rate, averaged to reduce noise and needs to achieve the target sensitivity to CO_2 specified in Deliverable 2.1. The emitter is modulated to decrease the baseline drift. The sensor response time is fast at ca. 1 s and so has a high bandwidth. Faster versions are under development with smaller IR emitter micro-hotplates.
- All circuits for 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 in order to communicate with the robot as requested by Taurob.

  The list of all sensor specifications is shown in Table 1.

Table 1: SmokeBot Sensor Specification

Component	**Sensor label**	**Target gas**	**Target parameters**	**Sampling rate**	**Resolution**	**Output**	**Sensor sources**
CMOS-based metal oxide resistive gas sensor	MOX-CO	CO	10ppm - 1000ppm resolution 5ppm	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^{o}C to +125^{o}C	10 Hz	Use 16-bit ADC	Analogue: 0-3V dc	CC2A23
Humidity sensor	HUMI	Humidity	0 to 100% RH (non-condensing)				
Particle sensor	PARTICAL	Particle density		10 Hz	Use 16-bit ADC	Analogue: 0-3V dc	Fairchild H21A3

The first version of the GSU has been fabricated and implemented. Fig.2 shows the photographs of the gas sensing unit and integration with the robot. The robot supplies 5V voltage to the GSU and communicates with the GSU through a serial communication protocol. The whole unit has been tested in a room filled with artificial smoke simulated smoke room. The last photograph shows the robot carrying the GSU as it enters into the smoke room. The initial integration with the mobile robot was successful, the communication was established and the acquired data are stored in the operating system of the robot.



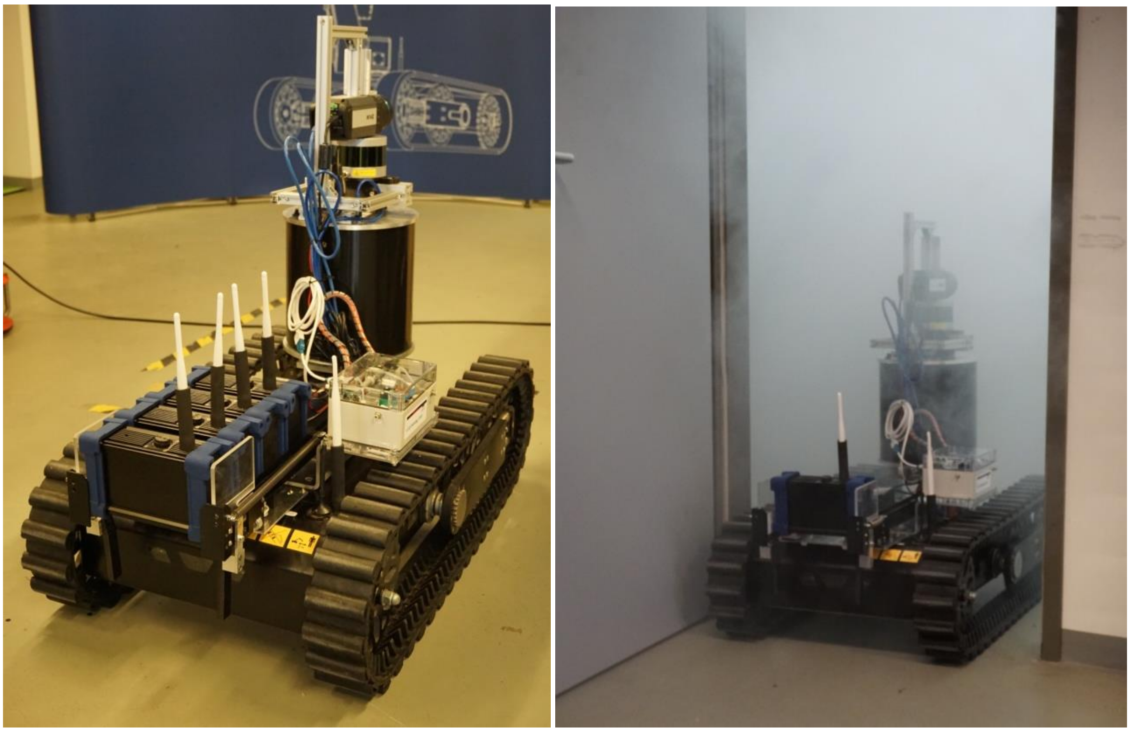
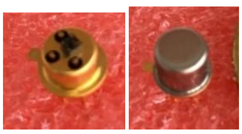


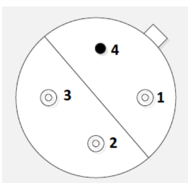
Fig.2 Photos of the gas sensing unit and integration with the robot

3. MOX gas sensor and its interface circuitry design

MOX gas sensors are designed and fabricated for the purpose of detecting oxidizing/reducing gases such as CO and NO_2in air, which are labeled as MOX-CO and MOX-NO_2, respectively. Pt/Pd doped SnO_2 sensing material is deposited onto the micro-hotplate to form the MOX-CO sensor. WO_3 sensing material is deposited to the micro-hotplate to form the MOX-NO_2 sensor. The package, pin configuration, controlling and measurement mechanism of the two sensors are same. The MOX films need to operate at around 350^{o}C to (i) enhance response time/bandwidth and recovery time, (ii) reduce water cross-sensitivity and (iii) enhance selectivity.

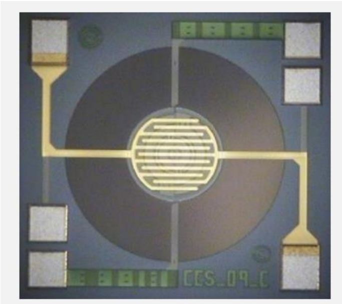
Both MOX sensors in GSU are based upon a commercial high temperature micro-hotplate manufactured using a Micro-electro-mechanical system (MEMS) process. The micro-hotplate is formed from a circular dielectric membrane, supported on a silicon substrate, with a central tungsten heater, produced by a Deep Reactive Ion Etch MEMS process. The inherently low thermal mass allows for rapid heating to high temperature (>500^{o}C), enabling pulsed mode operation at high frequencies and significantly reducing power consumption. Fig.3(a)(b) show the photo and pin configuration of MOX sensors. Fig.3 (c)(d) show the layout of the micro-hotplate and electrical characteristics of the sensor.





Pin	Function
1	Sensor+
2	Heater+
3	Sensor GND
4	Heater GND

*(a)***Photos of the sensor** *(b)***Pin configuration**



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

(c)Layout of micro-hotplate (d)Electrical characteristics of MOX sensor

Figure 3: MOX gas sensors and their properties

3.1 Heating control circuit

Metal oxide sensing material shows sensitivity to redox gases at a high operating temperature via chemisorbed oxygen states. Hence, all MOX sensors include a heater to set/control the operating temperature. The suggested operating temperature for the two sensors is 350°C. Different sensitivity to gases is shown at different operating temperatures of the same MOX sensor. For the purpose of flexible control and decreasing the effects of environmental temperature variation, the heating of micro-hotplate must be automatically controlled with the feedback of environmental temperature. Fig.4 shows the whole interface circuit of two sensors including the heating control circuit and sensor measurement circuit.

The MOX sensor interface circuit is designed to be compatible with the standardized metal semiconductor package - TO-5 package, which is used by the commercial micro-hotplate. A temperature diode is embedded in this sensor to monitor the operating temperature of the micro-hotplate. A current source (REF200) is adopted to generate the constant current for the diode voltage measurement. VDIODE1 and VDIODE2 are the two outputs of the temperature diodes to be connected with the micro-controller.

The Digital-to-Analogue Converter (DAC) is used to output signals to control the heating power of MOX sensors. DAC7612 is adopted to output two voltages V_{OUTA} and V_{OUTB}. V_{OUTA} and V_{OUTB} are divided by 10 and then used to control the heating current through the heater of the sensors. The heating current through the heater is set as:

$$I_{HA} = \frac{V_{OUTA}}{100}, I_{HB} = \frac{V_{OUTB}}{100}$$

V_{OUTA} and V_{OUTB} are in the range of 0 – 4096 mV. Therefore, the I_{HA} and I_{HB} are controlled in the range of 0 - 40.96 mA, which is in line with sensors specification.

The temperature of micro-hotplate (or the sensor) is monitored online. If the sensor with temperature diode is adopted in the unit, the heating temperature is detected by the VDIODE1 and VDIODE2 directly. However, a practical approach is proposed to deal with the case of sensors without temperature diodes, such as the CCS301. The CCS301 sensor is adopted in the first version of the module indeed. The approach is based on the sensitivity of heater resistance to temperature. As a tungsten resistor, the resistance of heater is sensitive to temperature and can be used as a temperature sensor. The heating voltage cross the heater is obtained by

$$V_{HA} = A5V - VH1 = (V_{A5V} \quad - VHEAT1) \times 2$$

$$V_{HB} = A5V - VH2 = (V_{A5V} \quad - VHEAT2) \times 2$$

where V_{A5V}, $VHEAT1$, $VHEAT2$ are measured separately. The resistance of heater is given by:

$$R_{HA}(T_A) = \frac{V_{HA}}{I_{HA}}, R_{HB}(T_B) = \frac{V_{HB}}{I_{HB}}$$

The dependence of heater resistance on temperature is obtained from the datasheet of micro-hotplate. For CCS301 series, the dependence is shown in Fig.5. The temperature of micro-hotplate is determined by the fitted curve and equation.

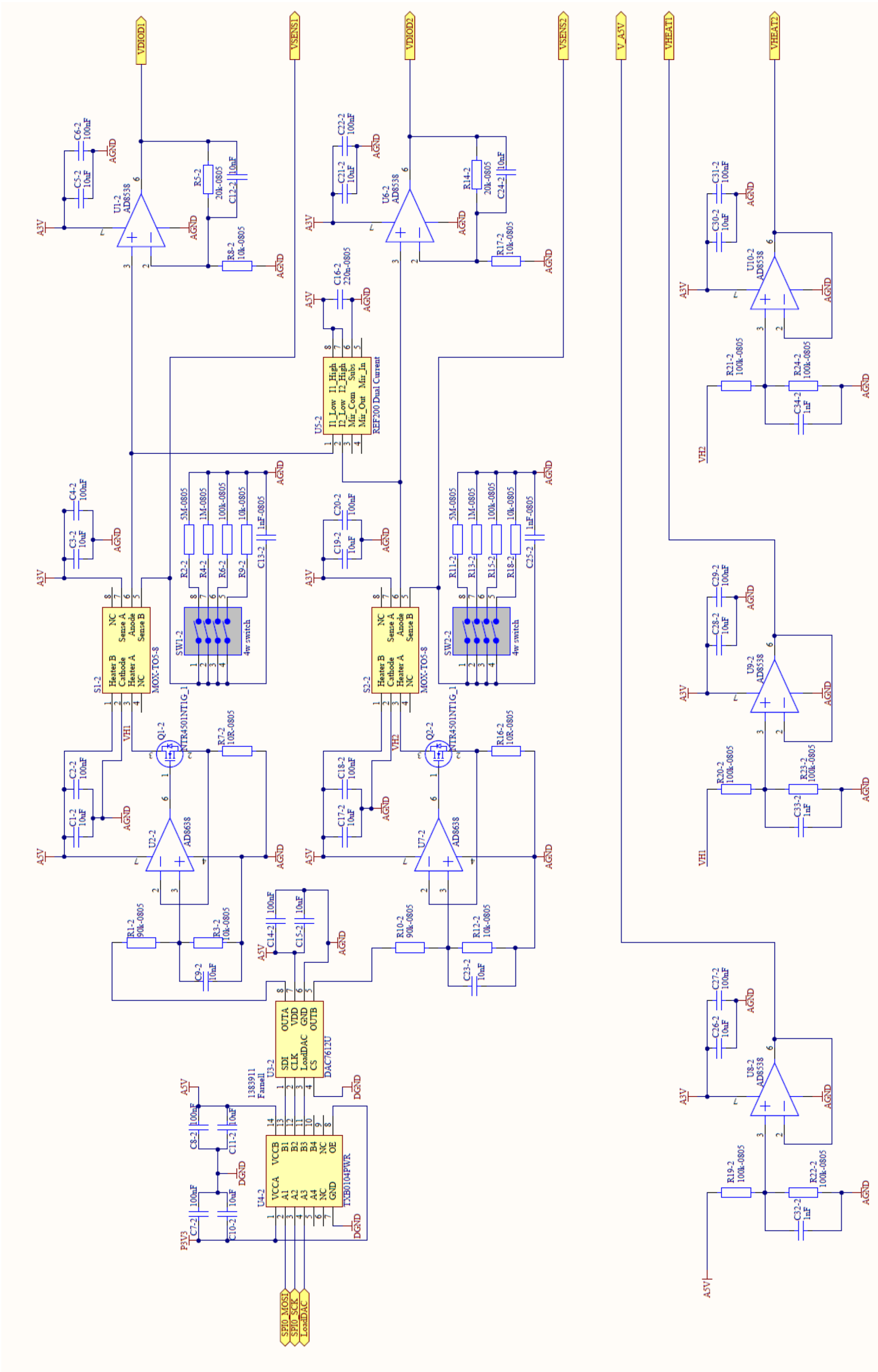


Fig.4 Interface circuit of two MOX gas sensors

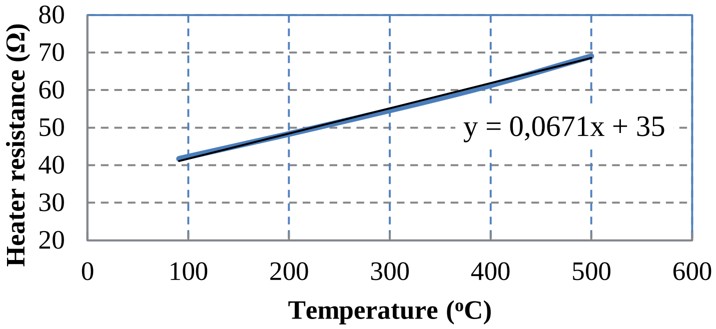


Fig.5 Dependence of MOX heater resistance on operating temperature

The monitored temperature of micro-hotplate is taken as a reference of adjusting the output control heating current. A feedback control loop in combination with the PID (Proportion Integration Differentiation) algorithm is implemented in the micro-controller based on the interface circuit. This control method is also important in order to decrease risks of high temperature damage of the sensors in real-life situations.

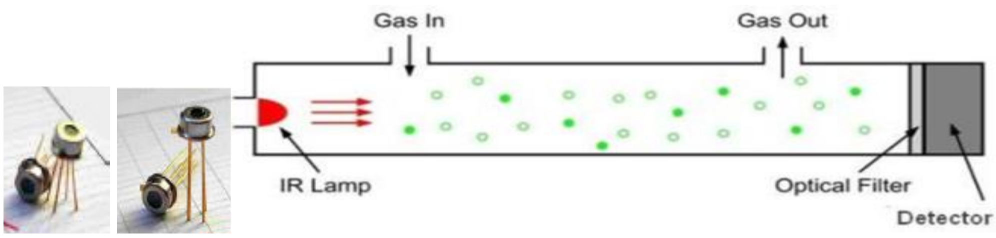
3.2 Sensor measurement circuit

To improve sensitivity and selectivity of MOX sensors to CO and NO_2, Pd/Pt doped SnO_2 and WO_3 are deposited onto the micro-hotplate as the sensing film. The resistance of sensing film varies from several kΩ to MΩ and is sensitive to temperature. Therefore, the sensor resistance is obtained through a voltage divider circuit. Four resisters of different values are selected as the load resistance and chosen by a 4-place switch. The voltage over the load resister is acquired as VSENS1 and VSENS2 for two sensors separately, which is shown in Figure 4.

4. NDIR gas sensor and its interface circuitry design

A Non-Dispersive Infrared (NDIR) sensor unit has been developed to detect high levels of CO_2 in air with a high bandwidth of 1 s.

In order to increase the selectivity of emitting infrared radiation at the desired wavelength (~4.26 μm), plasmonic structures were studied and the final emitter is packaged as the CCS102 series IR source shown in Fig.6 (a). Thermopile sensor HMS-J21-F4.26 (Heinemann) is chosen as the infrared detector. A single sensor with filter F4.26 is shown in Fig. 6 (b). The NDIR sensor does show sensitivity to ambient temperature and humidity (and particle density). Hence to reduce the effect of changes in air temperature, humidity and particle density, a dual sensor of this type is further studied which contains a reference channel with a filter F3.91. .



(a) **Photo of one type of emitter** *(b)* **Photo of one type of single detector** *(c)* **NDIR sensor operation diagram**

Fig.6 NDIR sensors and working diagram

To further reduce the influence of noise and ambient temperature on the detector, the emitter is driven by a modulated sine wave signal. Two kinds of sine wave generators are adopted, which are a MiniGen board and the SiTime 1534 chip. The two ways could be selected by the 2-position switch. MiniGen board with AD9837 waveform generator is selected in the first version of GSU. The board communicates with the micro-controller by SPI1 port. The output wave is then used to drive the emitter via a current driving circuit, which is shown in Fig.7.

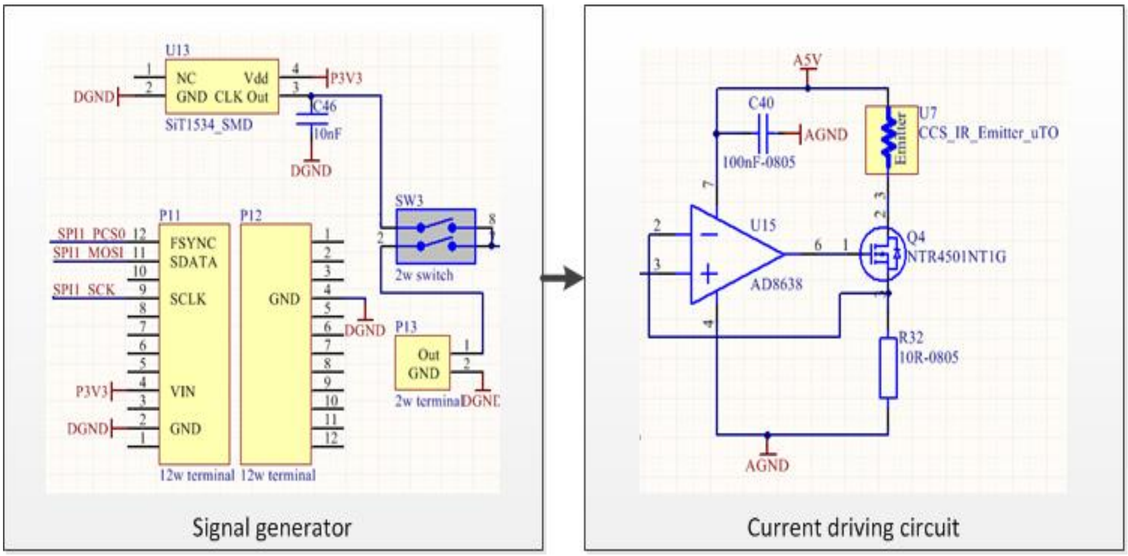


Fig.7 Interface circuit design of emitter

For the detector part, an amplifier and a band-pass filter are designed and shown in Fig.8. The processed voltage is then acquired by the ADC of the micro-controller. The acquired signal is then processed digitally using a FFT to remove the unwanted effects related to ambient temperature, humidity and other noise sources. Only the dynamic waveform corresponding to the modulated frequency is extracted out as the sensing signal to CO_2.This method reduces the bandwidth of the signal and hence reduces the voltage and current noise from the sensor/circuit. Further work is being carried out for faster modulation of the IR emitter to reduce noise and more importantly to further increase the bandwidth of the sensors.

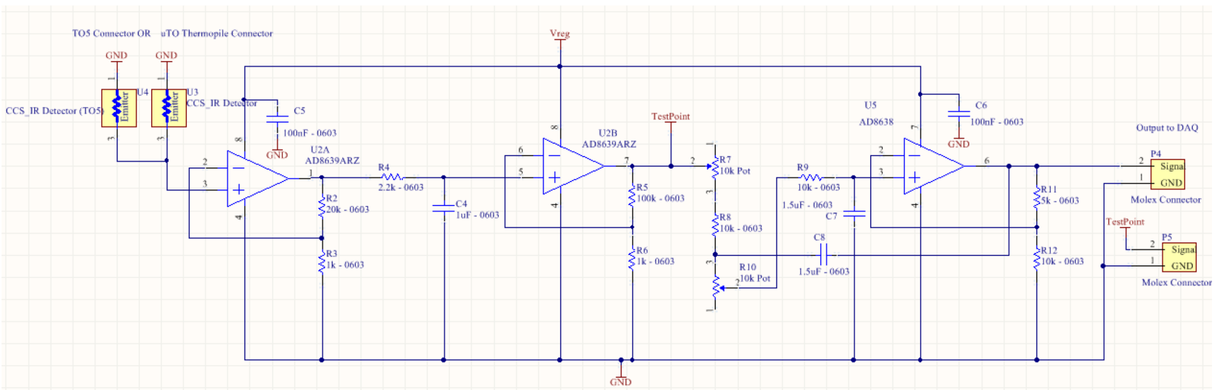


Fig.8 Interface circuit design of detector

A dedicated tube designed for the NDIR sensor and housed in the module separately from the main gas chamber is shown in Fig.9. It is beneficial for transmitting the infrared light and improve the sensitivity to CO_2.

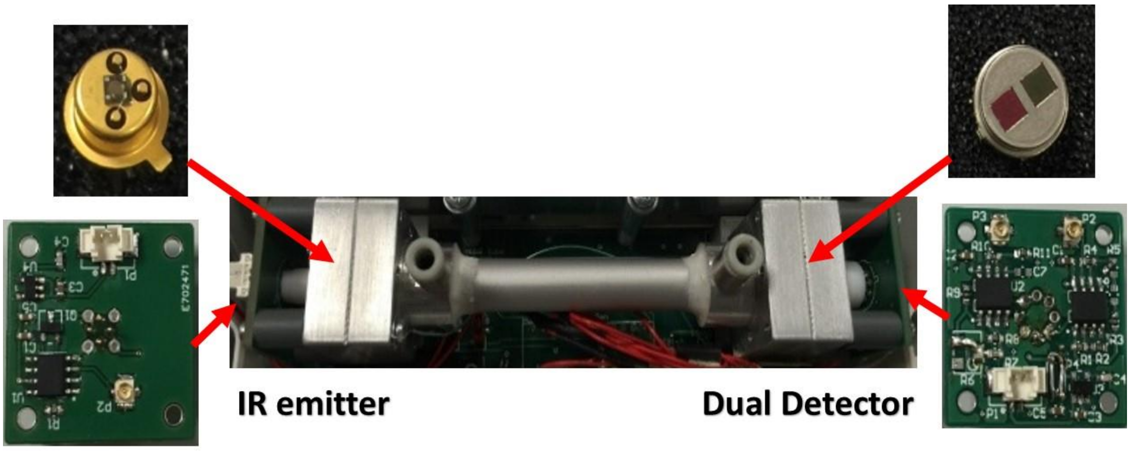
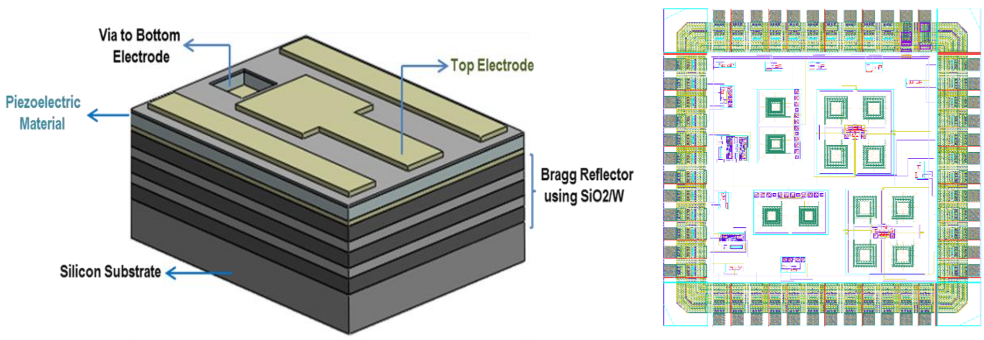


Fig.9 NDIR tube, emitter and dual detector and their circuit boards

5. SMR gas sensor and its interface circuitry design

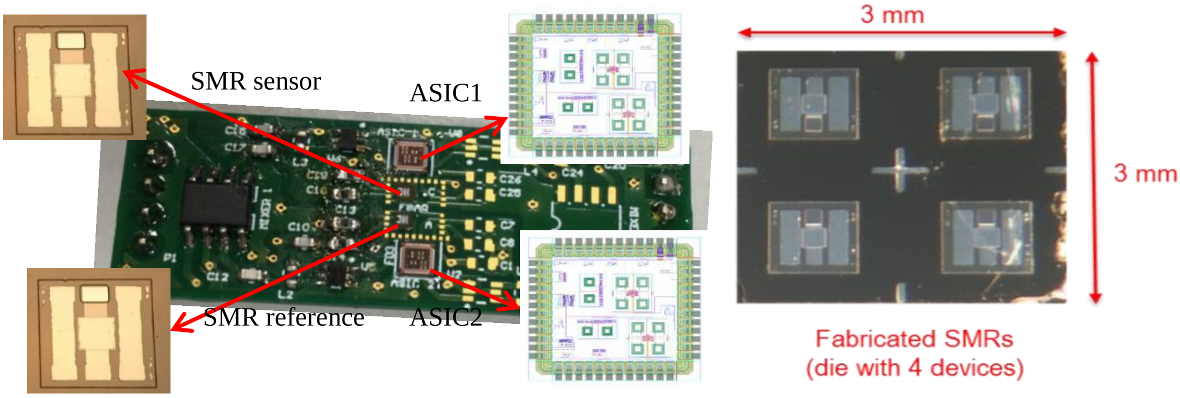
A new, low power, high frequency (970MHz) CMOS-based SMR sensor has been developed for VOC monitoring. The schematic of the SMR sensor is shown in Fig.10 (a). Specific polymers tailored to target the VOCs of interest within this project are coated onto the sensing area of the SMR chip. The target VOC is adsorbed into the sensing film resulting in a decrease of the resonant frequency of the sensor through an increase in mass density loading. The class and concentration of a target VOC can be determined from change in sensor frequency and multi-variate data processing. An SMR chip without a polymer is employed to act as a reference sensor and help remove common mode variations.

The dual SMR sensor signal is processed with a tailored CMOS ASIC. Fig.10 (b) shows the layout of the proposed ASIC chip. It is designed to process two SMR sensor signals and deliver a differential output. The ASIC chip is wire bonded directly to the PCB interface board. Fig.11(a) shows the photo of PCB with two separate SMR chips and two ASICs. The signals are mixed, amplified, filtered and compared resulting in a square wave. The frequency of the square wave is measured by the micro-controller, which is in the range of several kHz to several MHz. Fig.11 (b) shows a photograph of fabricated 4-unit SMR array.



(a) Schematic of SMR sensor *(b)* Layout of the ASIC oscillator chip

Fig.10 Schematic of a SMR sensor and the photo of the ASIC oscillator chip layout



(a) **Photo of the PCB with SMR sensors and corresponding ASICs***(b)***Photo of fabricated 4-SMR sensor array**

Fig. 11 Photograph of the SMR interface board and fabricated 4-unit SMR array

The ASICs were initially designed to include a number of oscillators and mixer configurations. These have now all been tested and the best ones are being used to design a new smaller ASIC chip that will remove the need for an external amplification and mixer. The new chip will be taped out in August with a fabrication date of October 2016. The AMS foundry will again be used for the chip fabrication in standard 0.35 um CMOS technology.

6. Temperature and Humidity sensor

Temperature and humidity are two critical parameters in the application scenario with potentially hot environments, such as fire fields, not only for the robot, but also for the temperature and humidity compensation for other sensors. The ambient temperature and humidity are measured in the GSU by a commercial ChipCap2 sensor from GE. The CC2A23 is selected as it is analog based, with an error lower than 2% and can work at 3.3V.

The interface circuit is based on its referencing circuit from data sheet, which is shown in Fig.12. Humi_sens and Temp_sens are connected with the ADC ports.

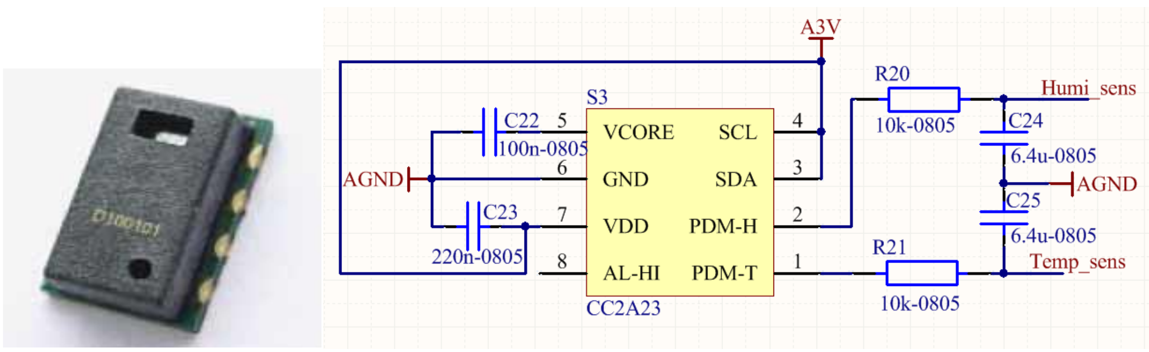


Fig.12 Photo of the Temp. & Humi. sensor and the schematic of its interface circuit

7. Airflow sensor

Airflow rate drawn into the pipe by the pump is detected to compensate the other sensors' output and to feed back to the pump control circuitry. An airflow sensor from Honeywell, model HAFBLF0750CAAX5 is selected. Its output is in the range of 0-5V corresponding to the flowrate range of 0-750sccm. The maximum current drawn by the sensor is 16mA (no load). The photograph of the airflow sensor and its detection circuit schematic are shown in Fig.13.

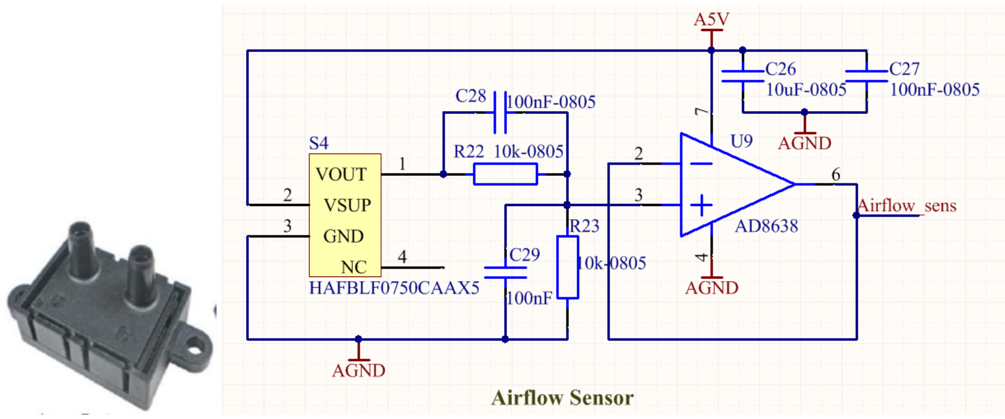


Fig. 13 Photo of the airflow sensor and schematic of its interface circuit

8. Smoke (Particle) sensor

There will be dense smoke and particles in some application scenarios, such as disaster fields that may cause damage to the sensor module. Therefore, a commercial light-based smoke detector has been employed within the unit. The optical switch modeled as H21A3 is selected as the smoke detector. It is a phototransistor based optical interrupter switch. To increase its sensitivity to smoke, an amplifier with baseline adjustment is included in the interface circuit, which is shown in Fig.14. The set point can be calibrated to close off the flow to the sensors when the smoke density is deemed too high. There is a filter to stop the particles but this could get clogged up if smoke levels are very high.

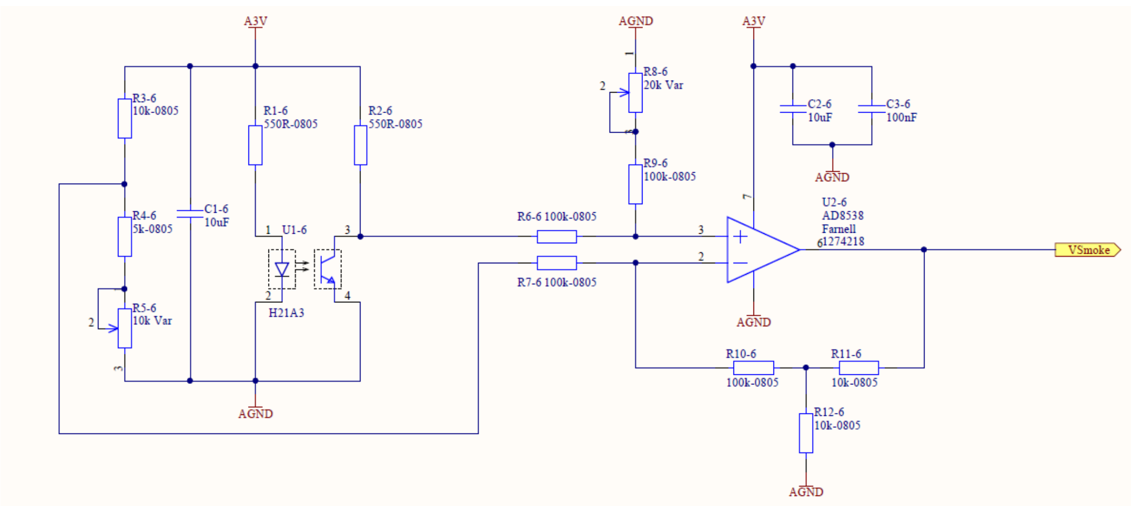


Fig.14: Schematic of the smoke detector

9. Micro-pump and its controlling circuit

The chosen pump is from Thomas Ltd, a 4.5V DC diaphragm pump, controlling flow rate in range of 0-850sccm. The rated power is 4.5V/165mA. The pump needs a high current driving circuit and a variable controlling voltage. A power amplifier chip OPA569is selected to drive the pump. Its highest output current could reach 2A, and it requires low supply voltage of 2.7V to 5.5V. OPA569 consumes about 9mA.Two times amplification is designed for the purpose of 4.5V range of control. The interface circuit schematics shown in Fig.15.

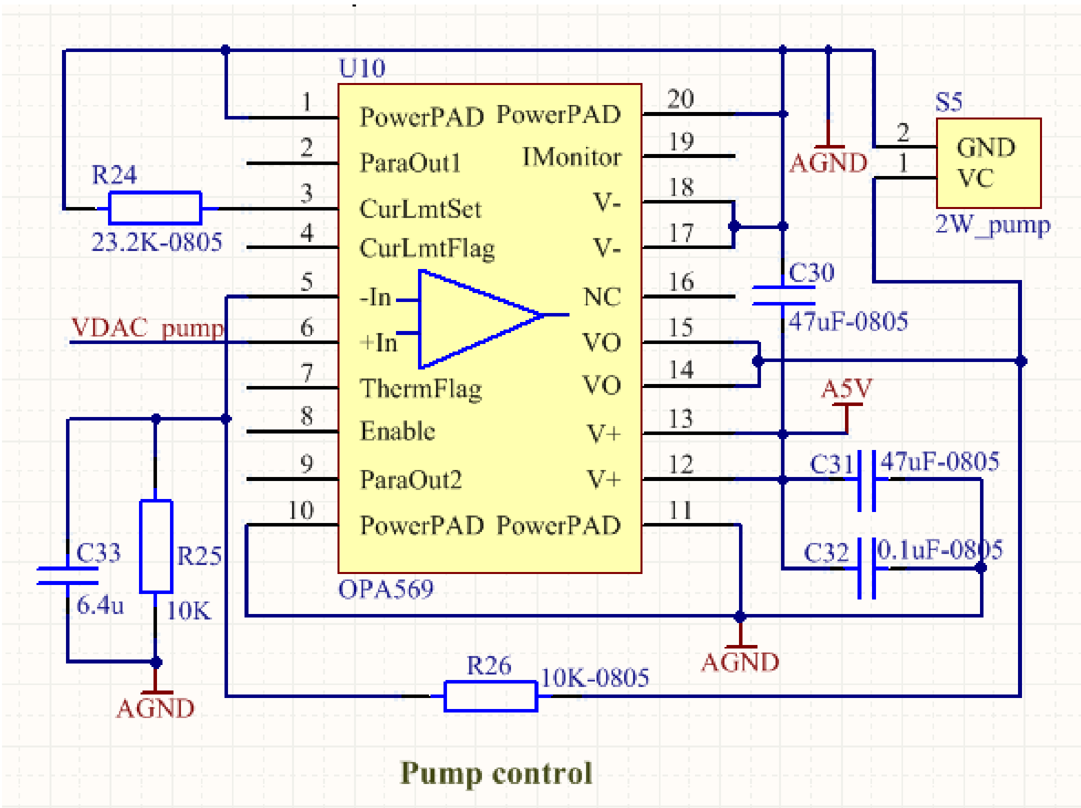


Fig.15: Schematic of the smoke detector

10. Micro-valves and their interface circuit

High density smoke or particles, high temperature in the real fire scenarios could pose a risk for the CMOS based sensors. Therefore, it is necessary to protect the critical sensor components from the dangerous ambient smokes and micro valves are included in the unit to shut off the connection of inner pipelines with the outer air. Environmental parameters, such as smoke density, temperature distribution and gas concentrations are different at various altitudes in the disaster space. For the purpose of obtaining parameters at two heights simultaneously with one unit, two valves are designed to locate at the inlet of the pipe, one is connected with the pipeline at lower height and the other one is connected with the pipeline at higher height. The two valves work alternatively and the gas information at two levels of height can be obtained simultaneously by a unit. The third valve is located at the outlet of the pipe. When the robot enters into high risk areas, the valves will be closed to protect the sensors in the chamber.

5V operated LFA series solenoid valves (Lee Company) are selected for this purpose, with maximum power consumption is 780mW. Fig. 16 shows a photo of the valve and the interface circuit schematic for the three valves.

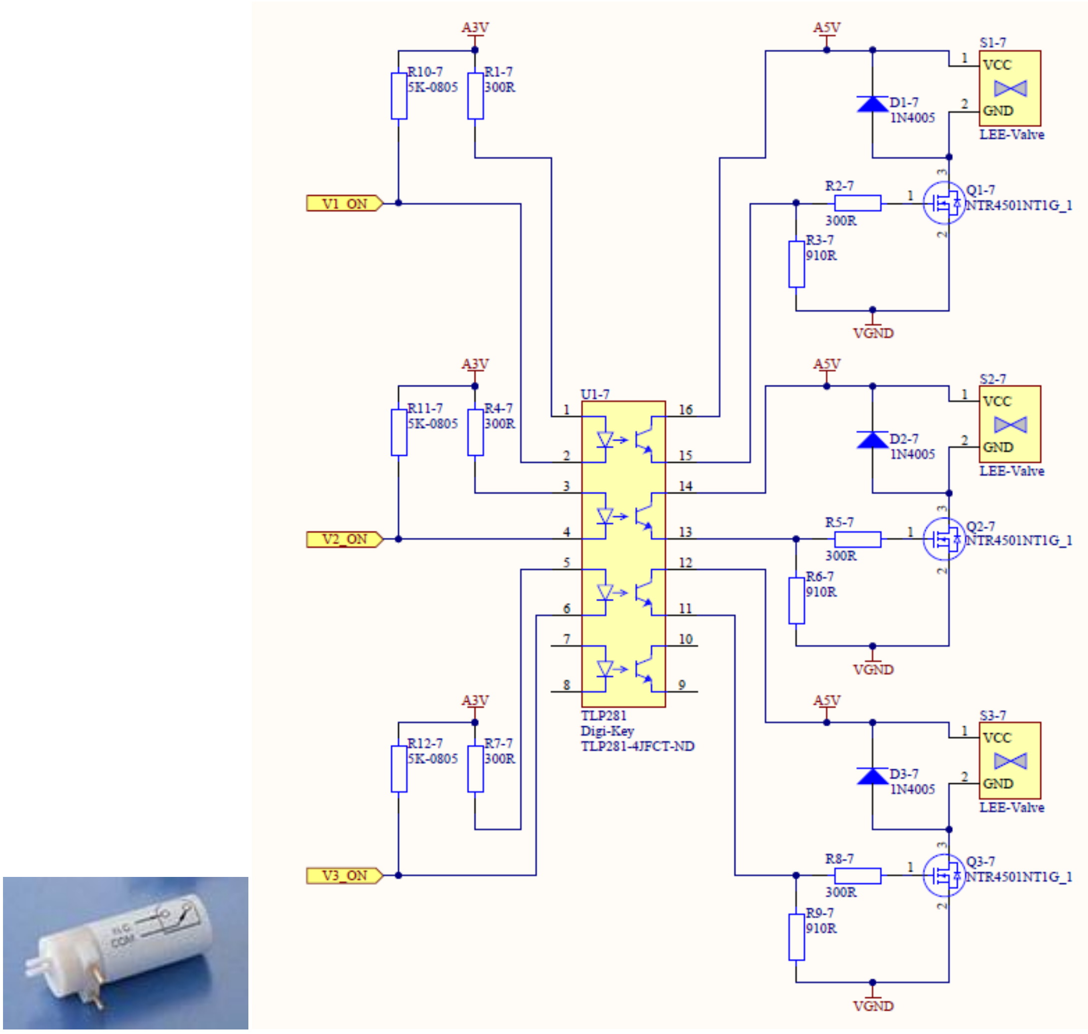


Fig.16: Photograph of the valve and the schematic of its interface circuit

11. Micro-controller

A Freescale FRDM-KL25Z micro-controller board is employed due to its low price and high performance. It is available as a single chip implementation for high volume application. The KL25Z contains a 32-bit ARM cortex - M0+ micro-controller clocked at 48 MHz, with on chip peripherals such as timers, ADCs and communication interface modules. Flexible I/O port configuration makes it easily to adapt to the SmokeBot application.

The FRDM board is used as the major development board. All the sensor voltage signals are acquired by the 16 bit ADCs. The frequency signals are acquired by the timers on the board. The RS232 communication port is designed based on its UART port. Two SPI ports are used for the control of a DAC chip and the miniGen board separately.

12. Power supply circuit

The total unit can be powered by 5V or 7-9V power source. Three kinds of voltages are used within the unit: analogue 5V, analog 3.3V and digital 3.3V. Maximum current at 5V of the unit is about 820mA. The schematic of power supply circuit is shown in Fig.17.

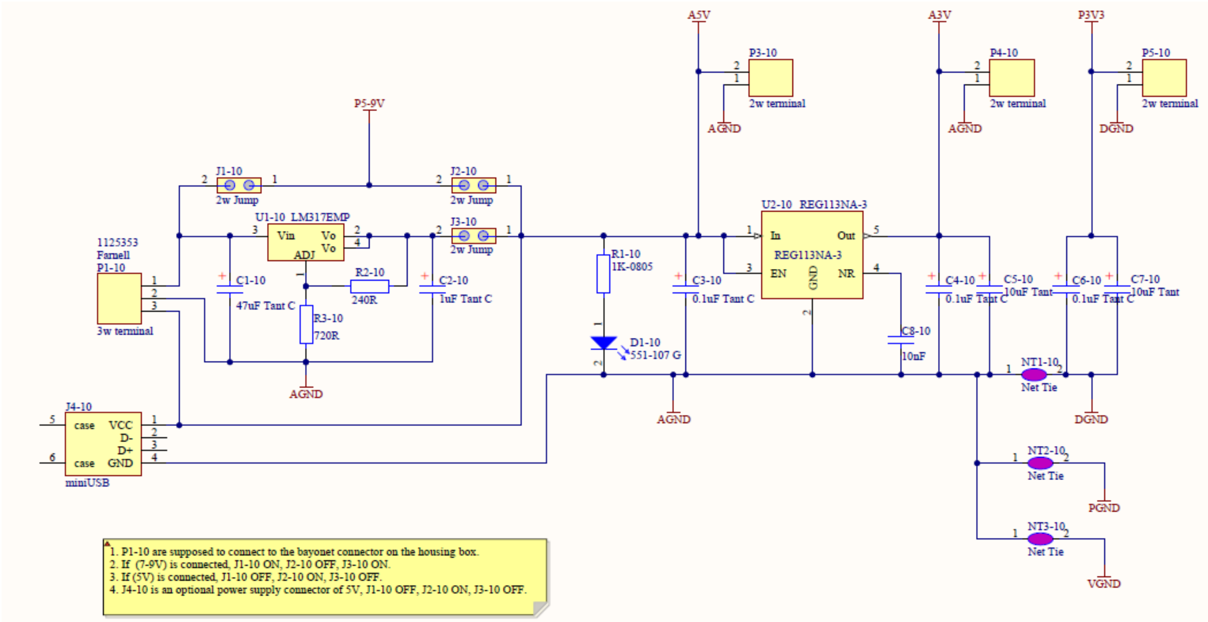


Fig.17: Schematic of power supply circuit

13. Conclusions and Future Development/Deliverables

A first generation Gas Sensing Unit (GSU) has been designed to house fabricated HBW sensors and integrated with the mobile robot based on the envisaged application scenario.

All the key sensors and controllers, including two MOX sensors, two SMR sensors, one NDIR sensor, one temperature and humidity sensor, one smoke sensor, one airflow sensor, one pump, three solenoid valves and the micro-controller board, as well as their interface circuitry have been described in detail in this deliverable.

The GSU has been integrated onto the robot platform and deployed in the artificial smoke room. The initial results of the integration were promising demonstrating the effectiveness of the design and implementation of the GSU.

The MOX gas sensors are relatively slow due to the flow dynamics. Signal filters are being developed that will enhance the response time from 10-20 s to 1-5 s. These will be reported in the next deliverable.

The SMR sensors are faster than the MOX and their bandwidth is determined by the operating frequency and thickness of the polymer coating. The new SMR used in this project operate at much higher frequency than the previously reported surface acoustic wave resonators (SAWRs) and thinner polymers are being tested with response time of 1-5 s. We are also designing and SMR with an integrated heater to further enhance the response. Again filters can be used to get response times of less than 1 s.

The optical NDIR sensor has a modulated emitter and bandwidth filter to reduce the response time to less than 1 s. Further improvements are underway with smaller IR heaters with x10 faster response times and will be fabricated in the next 3 months.

Characterisation of the existing sensors based on the GSU has been performed and are being measured in the wind tunnel. The filters are being added to enhance the bandwidth to the 1s range or below for odour pulses in the plumes.

The responses of the HBW gas sensors to target gases and in the presence of interferences will be used as further references in development of 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 now due in M21. Models can be hosted remotely to save power and resources. However, the use of a micro-controller will allow local feature extraction if required. Wind tunnel results will be reported in the next deliverable.

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. Finally, a smaller generation of GSU will be developed with reduced dead-volume, smaller SMR and NDIR gas sensors and data processing to enhance the bandwidth to 1 s or lower level.