Measurement of atmospheric pollutants based on electrochemical sensors and digital signal processing

Rumen Yordanov[1], Rosen Miletiev and Emil Iontchev
[1]Department of Microelectronics, Faculty of Electronic Engineering and Technologies
Technical University of Sofia
8 KlimentOhridskiblvd., 1000 Sofia, Bulgaria
yordanov@tu-sofia.bg

Abstract –**The current paper discusses the design of the pollution and communication system which is capable to measure the H_2S levels in very low concentrations in ppb range. The system also reads the temperature and humidity values from the analog output values and send the measured values to the remote server via GSM/GPRS connection, which are stored in MySQL table for further analysis and visualization. This part represents the methods and algorithms to obtain the values of the analog inputs using digital signal processing of the data, measured by integrated 10-bit SAR ADC.**

Keywords– **H_2S measurements, temperature, humidity.**

I. INTRODUCTION

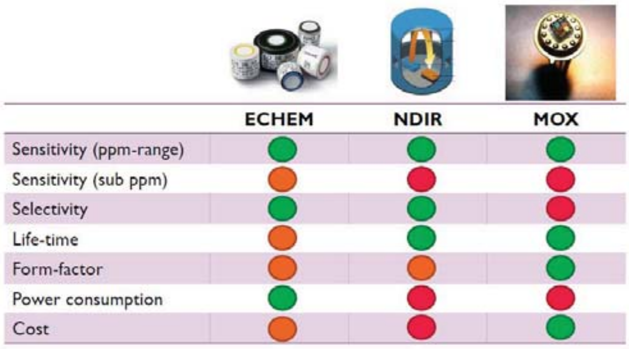
Air pollution is one of the biggest problem in the cities. In the most cases it’s induced by automotive, industrial or natural source. The advances in the microelectronics technology allows developing of smaller devices which are capable to measure environment parameters such as temperature and humidity and atmospheric pollutants like chlorides, NO_x, SO_x, CO_2 and hydrogen sulfide (H_2S). The hydrogen sulfide gas is commonly found during the drilling and production of crude oil and natural gas, plus in wastewater treatment and utility facilities and sewers. The gas also is produced as a result of the microbial breakdown of organic materials in the absence of oxygen. It irritates the mucous membranes of the body and the respiratory tract. Repeated exposure over time to high levels of H_2S may cause convulsions, coma, brain and heart damage, even death. The odor threshold is defined in the concentration range from 0.01 to 2.5ppm as the typical background concentrations are from 0.00011 to 0.00033ppm. According to the national standards the maximum air concentration is defined as 0.005mg/m^3 (for 60-minute exposure) or 0.003mg/m^3 (for 24 hour exposure) which corresponded to 3.6ppm and 2.2ppm respectively. Therefore the main requirement to the measurement system is to detect H_2S concentrations in the ppb range with resolution of 1ppb or lower.

The low-cost sensor are very attractive for the market but has some drawbacks such as measurement stability, sensitivity, selectivity, etc. but during the last years their characteristics are improved significantly. If they are combined with the information and communication system which is capable to send the measured data to the remote server, the real-time measurement may be accomplished. The mobile measurement of the air quality and gas concentrations is a very actual problem due to the great human mobility, pollution motion and the absence of measurement stations.

The current paper represents such type of measurement system which reads the data from the electrochemical sensor for H_2S and the environment temperature and humidity and sends the measurement data to the remote server with installed MySQL database. The proposed system produces a digital signal processing of the measured analog values to increase the resolution of the integrated ADC to increase the system sensitivity.

II. SYSTEM DESIGN

There are several categories of sensors currently available and the comparison study of the air pollution sensors [1] shows that there is no perfect sensor and the choice of the sensor type depends from the user needs (Figure 1). Due to their small form factor, metal oxide (MOX) sensors have been widely adopted to measure a wide spectrum of important air pollutants in the mobile platforms, but MOX sensors suffer from low selectivity and poor long-term stability especially when they are operated in atmospheres containing even at very low siloxanes concentrations [2].



	ECHEM	NDIR	MOX
Sensitivity (ppm-range)	🟢	🟢	🟢
Sensitivity (sub ppm)	🟠	🔴	🔴
Selectivity	🟢	🟢	🔴
Life-time	🟠	🟢	🟢
Form-factor	🟠	🟠	🟢
Power consumption	🟢	🔴	🔴
Cost	🟠	🔴	🟢

Figure 1. Comparison study of low-cost sensors

The electrochemical sensors are the second candidate to be implemented in the portable devices as they used for workplace and hazardous gas leak detection for decades. Nowadays, electrochemical gas sensors are available for just about any target gas, and they are used extensively in many stationary and portable monitoring applications. These sensors are low-power, robust and low-cost, and are based on amperometric sensor methodologies designed for sensing selected toxic gases at the ppm levels in the industrial environment. Continuous operation (over 10 days) at low relative humidity (<15%) and / or high

978-1-7281-2574-9/19/$31.00 ©2019 IEEE

temperatures (>40°C) can cause loss of sensor sensitivity (nA/ppm) in some sensors. Loss of sensitivity is in the most of cases temporary and the sensors can recover when exposed to the normal humidity conditions.

The electrochemical sensor system is based on 4-electrode H2S-B4 hydrogen sulfide sensor produced by Alphasense. It sensitivity varies from 1450 to 1900nA/ppm, response time up to 40s and it is capable to detect H_2S concentrations below 1ppm. The use of the Alphasense ISB circuit (Figure 2) reduces the noise to 1ppb which may be additionally reduces by the digital signal processing. The Individual Sensor Board (ISB) is designed for use with the Alphasense B4 family of four-electrode gas sensors.The sensor is connected to the digital part by ISB connector and RC lowpass filter to the integrated ADC (CH1IN and CH2IN on Figure 3).

Figure 2. ISB board

The digital part is based on 8-bit microcontroller PIC18F45K22-I/PT (Figure 3). It has built-in 2xI^{2}C interface as a part of Master synchronous serial port (MSSP) modules and 2xEUSART with an autobaud interface, which are connected to the GSM/GPRS modem with RTS/CTS hardware flow control and particulate matter sensor (PM connector) and lots of analog inputs which are multiplexed to the integrated 10-bit ADC. The used analog inputs are as follows (Figure 3):

- AN10 – T/RB output from the external temperature sensor LGHTM-01A
- AN9 – H/TA output from the humidity sensor LGHTM-01A
- AN12 – analog output from the internal temperature sensor TC1047A
- AN8 – ISB analog output (first channel)
- AN24 – ISB analog output (second channel)

The analog inputs are sampled by integrated 10-bit ADC and stores as 16-bit values. As the digital signal processing is accomplished the data are sent to the remote server via GPRS connection. This connection is fulfilled by the communication part which is based on Quectel M66F GSM/GPRS modem (Figure 4) and features GPRS class 12 and is distinguished with an integrated TCP/UDP, FTP and PPP protocols. The system connectivity is provided by the integrated chip-antenna WE-MCA 7488910245 for the frequency range 2400-2500MHz (Bluetooth module) and external GSM antenna via female SMA connector.

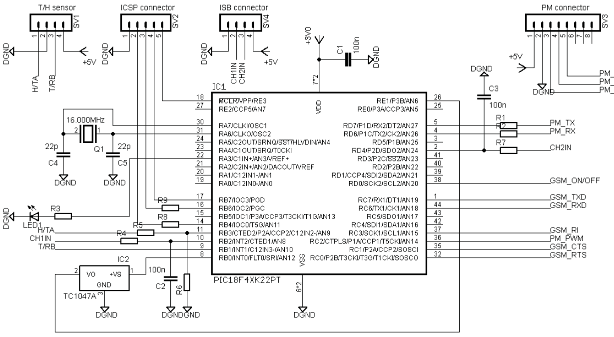


Figure 3. Digital part

All system blocks require different power supply levels. For example the ISB board requires power supply in the range from 3.7V to 6.4V, the communication part with GSM/GPRS connectivity requires power supply range from 3.5V to 4.6V while the serial communication with the microcontroller requires levels from 2.5V to 3.0V.

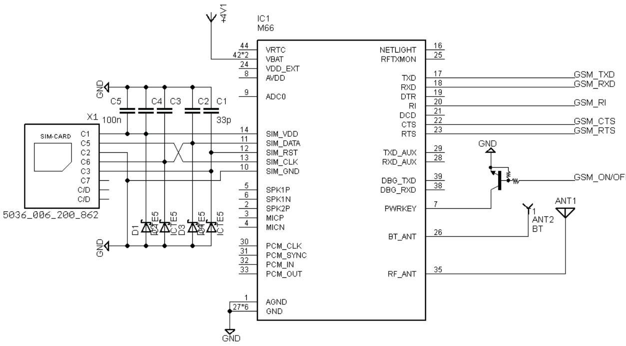


Figure 4. Communication part

The power supply of the digital part may be set from 1.8V to 3.6V. To meet all these requirements, the following power supply values are chosen:

- ISB power supply – 5V
- Communication part power supply – 4V
- Digital part power supply – 3V.

As the system is powered by 220VAC, a specially designed power supply is fulfilled to obtain the above mentioned power supply levels. The main power supply operates over a universal input range (85 VAC to 265 VAC) and provides two isolated outputs from the two secondary transformer windings (Figure 5).

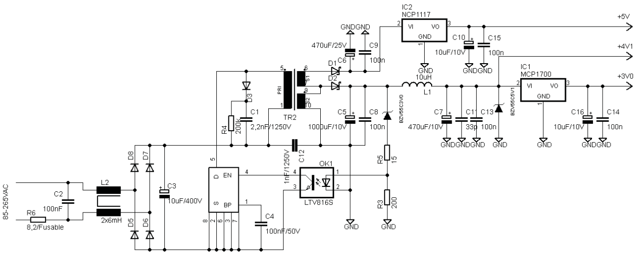


Figure 5. Power supply schematics

Operation at 132 kHz allows the use of a smaller and lower cost transformer core like EE16 for 10 W of output power. The first secondary winding is rectified and filtered by D2 and C5. Switching noise filtering is provided by L1 and C7. The 4V output is sensed by OK1 and BZV55C3V0 Zener diode. R3 is used to ensure that the Zener diode is biased at its test current and R5 centers the output voltage at 4V.The second secondary winding is rectified and filtered by D1 and C6. It provides approximately 8.5V output. The 5V and 3V outputs are realized using the LDO regulators NCP1117 and MCP1700 respectively.

III. DIGITAL SIGNAL PROCESSING ALGORITHM

The digital signal processing algorithm is based on filtering and smoothing of the measured data. It consists of the following steps (Figure 6):

- Step I – read of analog channels AN8 and AN24 which are connected to the first and second ISB channel respectively by sampling of the input analog signal with 50Hz sampling frequency (20ms sampling interval). The both channels are multiplexed every 10ms and the ADC result is stored in 128 byte buffers as 16-bit values.
- Step II – as the buffers are full, each buffer is copied in an additional buffer for the bubble sort procedure. When the sorting procedure is accomplished the first and the last 32 samples are rejected and only the middle 64 samples are averaged to obtain the median value.
- Step III – the calculated average value is passed through 1D Kalman filter which is used as a smoothing filter.

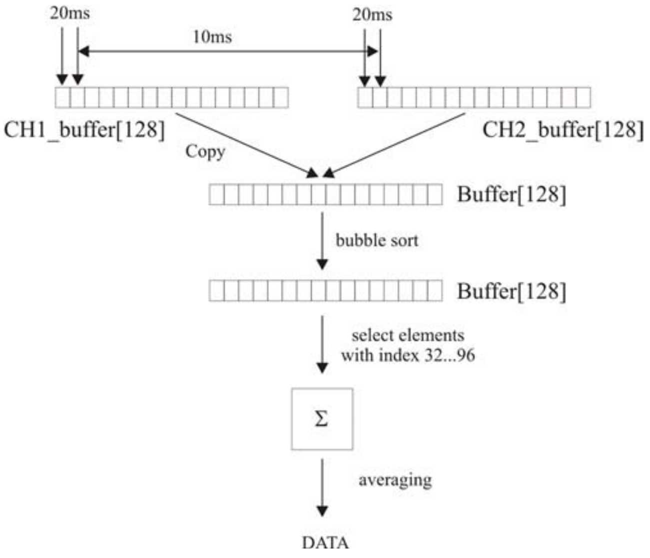


Figure 6. Digital signal processing algorithm

These three steps realized the median filtering – averaging – smoothing procedures and are easily implemented in 8-bit microcontrollers. Also the oversampling technique allows to increase the resolution of the integrated ADC from 10-bit to 13-bit according to the noise reduction by the averaging samples [3-4]:

$$f_{oversampling}=4^N.f_{Nyquist}$$

As the oversampling frequency is 64 times higher than the required Nyquist frequency, the ADC resolution is improved by 3 bits.

The great advantage of the integrated ADC is the possibility to select the source of REF+ input. It may be connected to the power supply (+3.0V) or to the internal fixed voltage reference (FVR) block, whichis a stablevoltage reference, independent of power supply voltage, with 1.024V or 2.048V selectable output levels. If H_2S concentration is low and the sensor output voltage is low then REF input is connected to 1.024V fixed voltage reference and the ADC resolution is 1mV/LSB. As the concentration is increased and the sensor output is higher the REF input may be connected to 2.048V reference voltage or to power supply. The REF+ input also may be dynamically changed from channel to channel. For example to achieve best resolution and a dynamic range it is possible to connect REF+ input to 1.024V reference input when ADC input is connected to the H_2S sensor outputs and to 2.048V reference input when ADC input is connected to the temperature and humidity sensor output. The H_2S sensor sensitivity is equal to 1.617mV/ppb and when the ADC resolution is selected as high as 1mV/LSB then the system sensitivity is better than 1ppb.

IV. RESULTS

The system performance is tested by 24h measurements of the H_2S sensor outputs and temperature and analog humidity sensor. All analog channels are multiplexed every 5ms and all analog data are stored in the corresponding buffers to be processed by the algorithm described above. As the buffers are full, the output voltage of the internal temperature sensor is measured and all data are sent to the remote server via GPRS connection. The measurement results are shown at Figure 7 and Figure 8.

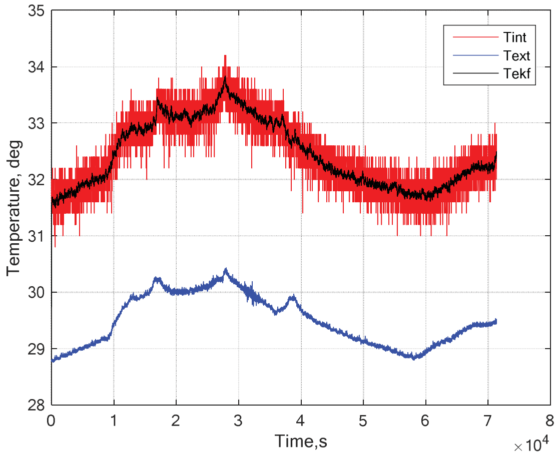


Figure 7. Temperature sensor outputs w/o Kalman filter

The implementation of the oversampling, median filter and averaging significantly reduce the noise (Figure 7) if the data of the external and the internal temperature sensors are compared. Due to the digital signal processing algorithm the external sensor data (Text) are very stable compared to the internal sensor data (Tint) which are sampled only one time. The noise of the internal sensor data may be reduced if Kalman filter is applied (Tekf) but the combination of median filter and averaging is more effective towards noise reduction.

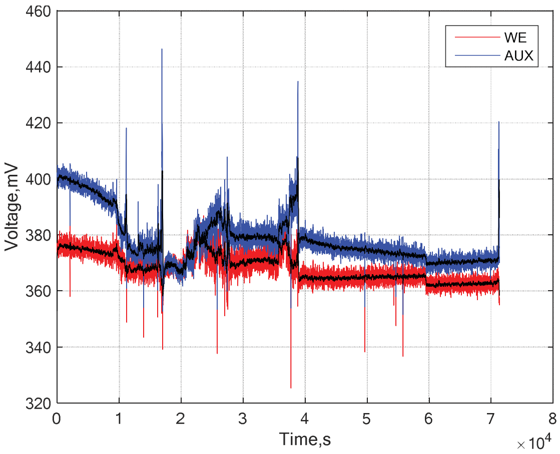


Figure 8. H_2S sensor output w/o Kalman filter

The applied Kalman filter algorithms is based on 1D Kalman filter implementation for Arduino [5], and the new value *x* is calculated according to equations:

$p = p + q;$

$k = p / (p + r);$

$x = x + k * (\text{measurement} – x);$

$p = (1 – k) * p;$

where:

q = process noise covariance, r = measurement noise covariance, p = estimation error covariance and k = Kalman gain.

As the gas concentration is changed slowly and the sensor response time exceeds 30s, for large noise reduction the Kalman filtering parameters are set to q = 0.125, r = 32 and p = 1023.

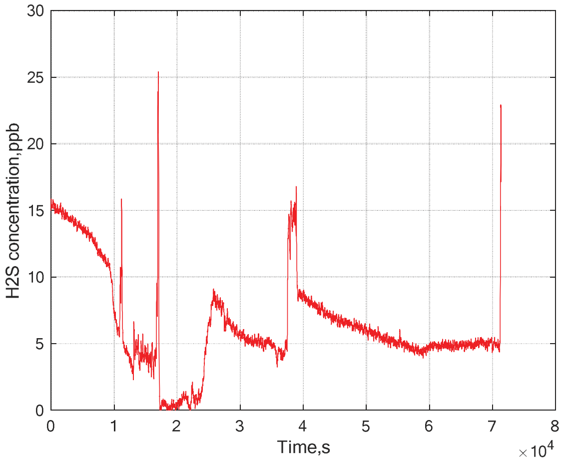


Figure 9. Detected H2S concentration

V. CONCLUSION

The H_2S sensor data (Figure 8 – WE and AUX) are also very noisy even the digital signal processing algorithm is applied. In this case the combination of the median filter, averaging and smoothing (black line) significantly reduce the voltage ripple. Therefore the H_2S concentration may be calculated according to the difference between the working and auxiliary electrodes and the sensor sensitivity and the results are shown at Figure 9.

The paper represents the digital signal processing algorithm which is applied to the data of the analog sensors such as electrochemical sensor for H_2S and temperature and humidity sensors. The used median filter and the data averaging may significantly reduce the measurement noise. This technique also allows increasing the ADC resolution of the integrated SAR ADC from 10 to 13-bits. The applied Kalman filter to the measurement data or to the algorithm results also is an effective way to additionally reduce the data noise. The implemented digital processing algorithm allows measurement of a very low gas concentrations in ppb range.

ACKNOWLEDGMENT

The authors would like to thank the Research and Development Sector and Faculty of Telecommunications at the Technical University of Sofia for the financial support.

REFERENCES

[1]. Marcel Zevenbergen, Sensors for air quality monitoring, https://www.kivi.nl/uploads/ media/55264396beb61.pdf

[2]. Daniel Rüffer, Felix Hoehne, and Johannes Bühler, New Digital Metal-Oxide (MOx) Sensor Platform, Sensors (Basel). 2018 Apr; 18(4): 1052

[3]. Silicon Laboratories, AN-118, Improving ADC resolution by oversampling and averaging, 2013

[4]. Texas Instruments, Application Report SLOA249, June 2017

[5]. A simplified one dimensional Kalman filter implementation for Arduino, https://github.com/bachagas/Kalman, accessed 08.2019