Eidgenössische Technische Hochschule Zürich
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Design of a Low-Cost Sensor Calibration Testbed

Semester Thesis

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Abstract

Low-cost gas sensors based on semiconducting metal oxides have been part of ongoing research in past years and by now provide an opportunity for air pollution monitoring at high spatiotemporal resolution. However, high accuracy of measurement can only be guaranteed through frequent recalibration, as the sensors are prone to errors such as signal drift. In this thesis, we explore the possibility of using portable gas generators as a source for known gas concentrations that can be used for sensor calibration. We researched two commercial products for generation of hydrogen and ozone respectively. As of yet, no viable method has been found that could be used for calibrating sensors.

Keywords: sensor calibration, low-cost gas sensors, air pollution sensors

Contents

Chapter 1

Introduction

1.1 Motivation

In recent years, an abundance of low-cost gas sensors became commercially available. These sensors still suffer from a range of flaws, not only in terms of measurement accuracy but also robustness in general. Commonly observed problems are:

- Dynamic Boundaries
- Non-Linear Sensor Responses
- Signal Drift
- Environmental Dependencies
- Low selectivity

The sources for these errors can be both external and internal. Non-linearity and signal drift are dependent on the sensing technique and materials used. Externally, humidity, temperature and the presence of other non-target gases can affect the sensors response. Through frequent recalibration, these flaws can be remedied. Yet for calibration, a more accurate reference sensor is usually required[1]. To circumvent the usage of expensive and immobile equipment, a portable testbed, where gas concentrations can be generated reliably, could be deployed alongside a sensor network. This provides the possibility to recalibrate the sensors on the spot at low cost. In the works described in 1.3, the assumption of available reference sensors is made. Access to such sensors might be limited, depending on external conditions (i.e. deployment in remote areas, budget, energy requirements, mobility).

1.2 Challenges

We try to answer the question, if commercially available gas generators can be used for calibration of low-cost gas sensors. For this to be possible, the generators should be able to reliably create one of the following conditions:

1. Generate a target concentration (absolute gas reference)
2. Generate reproducible sensor responses (relative gas reference)

For reliability, both scenarios require a suitable environment, where as many external influences as possible can either be controlled or compensated. Possible influences include:

- Variable gas generation due to manufacturing
- Chemical reactions of reference gas with the environment
- Humidity and temperature
- Cross-sensitivity of sensors with other ambient gases

In scenario 1, the calibration process could be approached in the same way as was done in other research presented in 1.3: Compare the sensor response with the absolute gas concentration and if a deviation is detected, recalibrate the sensor accordingly, using, for example, a regression algorithm.

In scenario 2, the sensors response to the gas generator would be recorded pre-deployment. The response can then be checked again after a sensible time frame. If it differs from the response recorded initially, signal drift can be detected. For this approach to be meaningful, the sensor would have to be calibrated against other known sources initially.

1.3 Related Work

The issue of calibration is recognized as a fundamental problem and has received more attention in the context of sensor networks in recent years. Similar ideas and experiments to the ones presented here, have been evaluated to examine possible usage of low-cost sensors in air quality monitoring. Castell et al.[2] used linear regression to calibrate AQMesh units[3]. The values were obtained in a controlled laboratory environment, tested in field experiments and the results compared to CEN (European Standardization Organization) approved gas analyzers. Sohn et al.[4] describe a calibration method also devised in a laboratory setting to counteract errors introduced by humidity. Propositions for self-calibration in mobile sensor networks have been made, such as 'CaliBree[5]'

in 2008 and 'On-the-fly Calibration of Low-cost Gas Sensors (Saukh et al.[6])'. All of these works have shown that performance can be improved significantly. Calibration therefore is essential for creating reliable measurements with low-cost gas sensors.

1.4 Roadmap

In Section 2 we explain our approach to test our generators and sensors. We also describe the equipment used and the reasons behind our choices. In Section 3 the results of our experiments are presented. In the last two sections (4,5) we draw conclusions from the results and provide an outlook for future work.

Chapter 2

Method

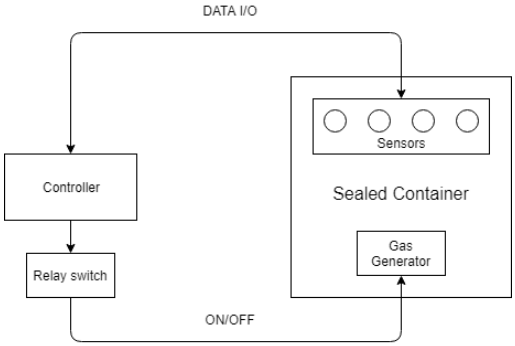


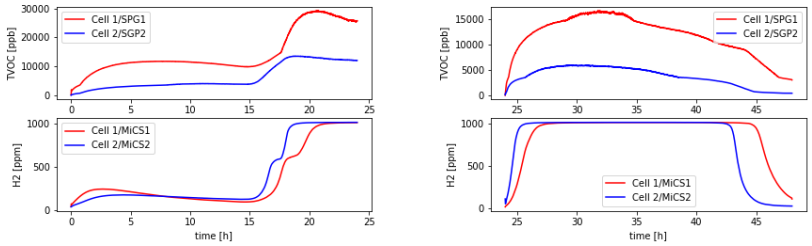
Figure 2.1: Experimental Setup

Commercial products usually do not disclose information apart from instructions for usage, assembly etc. In our case, expected values for gas output have been provided in both datasheets of the products we used. Yet there was no information about the variance between devices, degradation through depletion/usage and the outputs in relation to applied voltage. The setup for our controlled experiments is visualized in figure 2.1. We used a sealed box, where sensors could be exposed to the gases generated with no interference of external gas sources. We used a single micro controller for reading the sensor reports and to control the gas generators via a relay switch.

Initially, we used a simple setup of 2L plastic bags that contained both a generator and sensors. Over two 24h experiments, we exposed our sensors to a wide range of gas concentrations. This way, we could figure out appropriate time frames for the controlled experiments.

We then did multiple experiments, where the generators would be turned on for a fixed time frame. After each round, the box was ventilated manually by opening up the top. While this approach does not solve the issue of possible absolute measurement error (i.e. establishing a ground truth for the generated gas concentrations), low-cost gas sensors are known to exhibit errors due to var-

Figure 2.2: Photo of Plastic Bag with Sensors and Cell



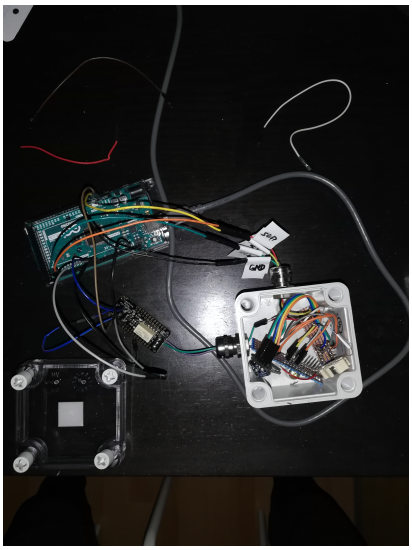
(a) First Test (b) Second Test

Figure 2.3: pre-calibrated sensor signals of SGP30 (Top), MiCS (bottom)

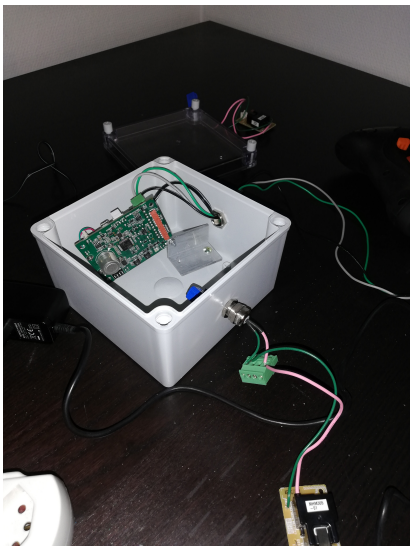
ious causes such as sensor aging, non-linearity and environmental influences[1]. These errors would still be visible even if absolute values for the concentration are not known.

2.1 Test Setup

All our sensors have been mounted on Adafruit[7] Breakout Boards. We used an Arduino Mega 2560[8] for reading the sensor reports and controlling the experimental variables such as duration and activation of gas generators. The



(a) Hydrogen Cell Test Setup



(b) Ionizer Module Test Setup

power supply of the ionizer module as well as the circuit for the hydrogen cell was controlled with a Latching Relay FeatherWing[9]. Both boxes are made of polycarbonate and the dimensions as well as the other parameters for the experiments are presented in table 2.1. For each test, the generators were turned on for the whole duration.

Sensor	**Gas**	**Box Vol.**	**Dur.**	**# Trials**	**Data P.**	**Temp. & Hum.**
SGP30	H_2	$400ml$	2h	30	2740	24C+/-1.5C
SM50	O_3	$2.25L$	0.5h	30	25	39%+/-2.5%

Table 2.1: Experiment data

2.2 Sensor specifications

The following low-cost gas sensors have been used in experiments:

- Sensirion SPG30[10][11]
- Bosch Sensortec BME680[12]
- ams CCS811[13]
- SGX Sensortech MiCS-5524[14]
- Aeroqual SM50[15]

All of these sensors use semiconducting metal oxides (SMO) as gas-sensitive resistors to detect VOC (volatile organic compounds) and are designed for indoor air quality monitoring. We relied mainly on the SGP30, since the chip comes with a baseline compensation algorithm and programmable error correction for humidity and temperature. This way, we could minimize the influence of these parameters on our test results. Furthermore, the chip provides two signals, where one exhibits a heightened sensitivity to hydrogen. This allowed us to expect better interpretable sensory responses to the hydrogen generated by the cell. The Aeroqual SM50 was used with the ionizer module. For temperature and humidity monitoring, we used a Sensirion SHT31[16].

2.3 Gas Generators

For our experiments, we tested two different means of generating gas:

- VARTA Hydrogen Cells[17]
- muRata MHM305 Ionizer module[18]

2.3.1 Hydrogen Cell

The VARTA hydrogen cell is a battery, that releases hydrogen gas upon connecting the poles with a discharge resistor. According to the manufacturer, typical gas output with a 100Ω resistor is $1ml/h$. Using this value and the volume of the box ($400ml$) one could expect a concentration of about 5000 ppm of hydrogen after two hours. This value exceeds the range of detectability of our sensors. This could also be seen in Figure 2.3b, where the MiCS-sensor response remains at its maximum value over almost the full duration of the experiment. Since the gas output can be controlled easily and no external power supply is needed, it is a promising candidate for usage with mobile sensor nodes. For our experiments we used 3 cells in total. Cell 1 was already in use before the controlled experiments for approximately 48 hours. Cell 2 and 3 were previously unused.

2.3.2 Ionizer

Monitoring ozone is commonplace in industrial workplaces and cities. It is a highly reactive gas that can be detrimental for human health at concentrations above 850 ppb[19]. Ionizer modules are commonly used for indoor air cleaning. They use high voltage to ionize air molecules. As a side effect, ozone is created during the process. For the MHM305, $0.04mg/h$ of ozone are described as a typical value. Comparing this value to the weight of air in the test box (4g) a simple comparison by weight would lead to 1000 ppm after an hour. Since

ozone is known to react with VOC components in the environment as well as converting back to oxygen, the rate at which the gas will actually form is not that easily predictable[20].

Chapter 3

Evaluation

3.1 Hydrogen Cell

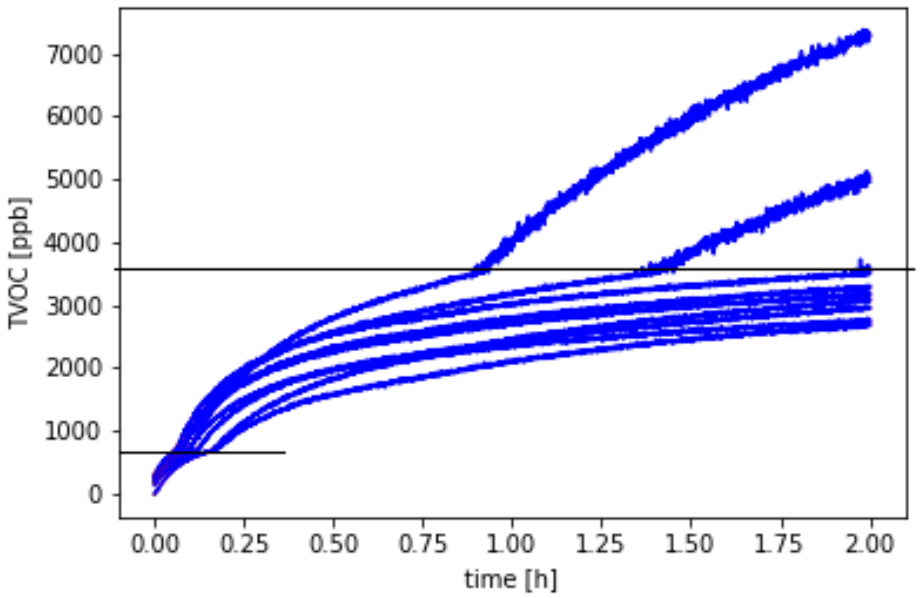
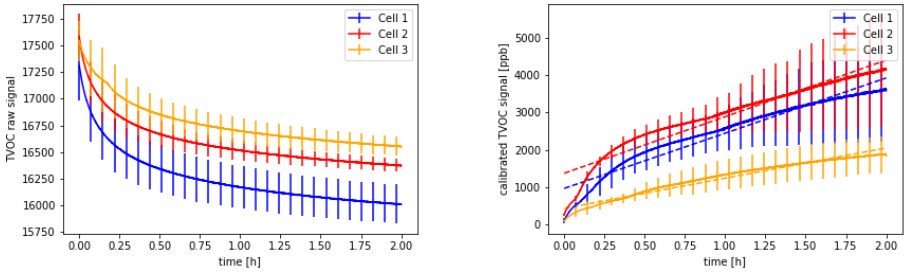


Figure 3.1: calibrated signal of 10 test runs

Looking at the raw signal values in Figure 3.2a, each cell did evoke a distinct response from the sensor. It can be seen, that later experiments exhibit decreased sensitivity (i.e. less change in signal strength). The sensor manufacturer provides research results about long-term stability of the SGP30[21] that indicates robust behaviour over much longer time spans than our 3 months of usage. Yet it has to be assumed, that the exposure to high H_2 concentrations did cause degradation in sensitivity. This in turn would also have influenced

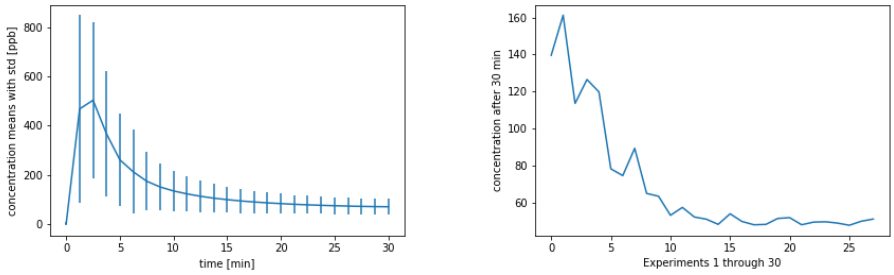


(a) raw TVOC signal (b) calibrated response to raw signals

Figure 3.2: Combined results from 30 experiments with hydrogen cells

the calibrated sensor responses depicted in Figure 3.2b. Given the information about the cell and data provided in Rüffer et al.[21], we expected an approximately linear increase in concentration. In Figure 3.1, the graph of ten separate test runs are shown. We see that the internal calibration parameters did affect the measurement at concentrations of 800 ppb and 3'600 ppb respectively. Yet considering the large variance in our test results, no conclusive statement about the actual concentrations can be made.

3.2 Ionizer



(a) mean with standard deviation (b) concentrations observed after 0.5h

Figure 3.3: Results from 30 experiments with ozone generator

In Figure 3.3a, one can see that initially, comparatively high concentration of the gas are observed. These numbers did exceed the recommended level of usage provided by the manufacturer. After this initial phase, the concentration converges to a lower value around 60 ppb. Since there is only a limited amount of oxygen available, the ioniser will only convert a fixed amount into ozone. The ozone then reacts with pollutants in the air as well as the polycarbonate from the test box. The concentration slowly decreases until an equilibrium is

reached. This point is determined by the initial amount of oxygen, the rate at which ozone chemically reacts with other pollutants and its conversion back to oxygen[20]. Figure 3.3b shows that the signal values after 30 minutes did drop to a considerably lower level within the first 10 experiments. It has to be assumed, that this is at least partly if not mostly due to signal drift. While the results presented in 3.3a do match our expectation, the high concentrations generated did most likely poison the sensitive SMO layer of the sensor.

Chapter 4

Conclusions

We explored two ways of generating gas for sensor calibration in a laboratory setting. Our experiments show that a wide range of concentrations can be generated, yet with our simple test equipment, a stabilization or direct control was not possible. It must also be assumed that several other influences disturbed our measurements:

- Sensor degradation and therefore signal drift did most likely occur within all our sensors, since the theoretical values for the concentrations acquired through estimation do most likely exceed the intended levels of usage.
- Air flow could affect the results, since hydrogen has a lower density and will rise to the top of the container. The sensors were not kept in exactly the same position for all experiments and might therefore have experienced different levels of exposure.
- While temperature and humidity did not change significantly during experiments, a slight influence cannot be ruled out.
- Using a testing environment made from polycarbonate will affect measurements, as they are a known source of VOC in indoor environments. The tests also have been carried out in ambient air. This introduces another variable that likely has not been the same over the duration of our experiments.

The measurements for the hydrogen cells overall were subject to large deviations of up to 50% compared to the average signal strength. Therefore using the signal as a reference for calibration would at this point not suggest an increase of performance. The test results acquired with the ionizer module show, that a comparatively more reliable concentration can be achieved, yet due to ozones reactivity, a suitable test environment must be chosen. Another possible drawback of this generation method is the presence of ions, whose influence was not further investigated.

The results lead to the conclusion, that for generating and detecting small amounts of gases, more sophisticated equipment is still needed. Predicting and estimating the interactions of gas with environment and measurement equipment, does require knowledge of chemistry. Therefore devising meaningful and stable test parameters has been a difficult part of this work.

Chapter 5

Future Work

It is clear at this point, that further investigation of this topic is required, since experimental results have been inconclusive at best. Too many external and internal variables could not yet be controlled. In the case of the hydrogen cell, one could imagine a pressure-based valve to be used for controlling the influx of hydrogen gas into the testing environment. This should still be achievable on a low budget and decrease the variance of the gas concentration due to manufacturing or degradation of the battery.

For testing purposes, a better automatable ventilation system should be used, since much time has been spent, manually setting up the testing equipment.

Both methods of gas generation examined were readily available to us at the start of the project and therefore chosen for our experiments. Other portable means of gas generation should be researched.

In this work, the aspects of examining generators and low-cost sensors have been combined. Separating the observation of generator output from sensor response via more reliable methods of verification should lead to more conclusive results.

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