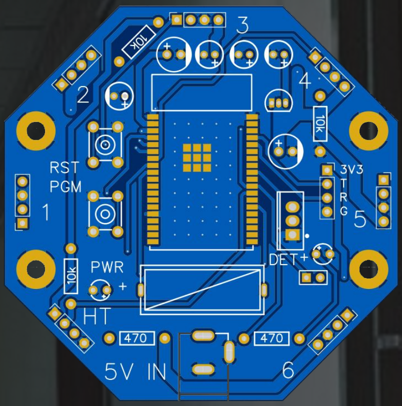
An electronic nose for solid stool detection

eNose - Hardware



Bachelor Graduation Project
Electrical Engineering

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Momo Medical

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eNose - Hardware

by

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Cover Image: hospital hallway with a wheelchair, retrieved from Getty Images

TU Delft

Abstract

This document reports details the development of a solid stool detection system. On behalf of Momo Medical - a TU Delft-based startup company - a device for detecting defecates by elderly people has been designed. The goal of the detection system is to detect solid stools by elderly patients wearing a diaper and to notify the nurses in a nursing home accordingly. The project has been organized and conducted in two groups: Hardware & Software. Our group has been in charge of the hardware. The other group has been responsible for the software. The main focus in this report will be the hardware design of the system.

This report contains: the analysis of the problem, the development of a solution, the design and the evaluation of the device in test. The developed device detects methane by means of multiple gas sensors, since methane is the main gas component released while defecating. Several iterations making a suited printed circuit board and case have been carried out, while taking aspects like safety, reliability and noise performance into account. The report concludes with a summary of main results and an outline of future work.

Preface

This thesis has been written in the context of the Bachelor Graduation Project. The project has been carried out in collaboration with Momo medical. Since the results of the project have been promising, the device will be tested in real nursing homes after the report has been handed in. The results regarding the implementation of the device in nursing homes will be presented during the final presentation.

We would like to thank Menno Gravemaker, CEO of Momo Medical and Thomas bakker, CTO of Momo Medical, for giving us the opportunity to work on this project, and supporting us in an enthusiastic and positive way. Furthermore, we would like to thank our supervisors prof. dr. Paddy French and dr. Massimo Mastrangeli for all the effective feedback and guidance during the project. Last but not least, we would like to express our gratitude to Mark Fijneman, Maxim Chin-On and Gabriel Yousef for the close and effective collaboration during the project.

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Introduction

For the Bachelor Graduation Project(BAP) of the BSc Electrical Engineering at the Delft University of Technology, a team of students accepted a technical challenge posed by Momo Medical [1]. Momo Medical is a small TU Delft-based company located in Yes!Delft. They provide and develop non-intrusive monitoring systems in the nursing sector. The project is a next step in expanding the functionality of an already existing product: The Bedsense. The BedSense is a system that consists of an under-the-mattress sensor, a hub, and a software application. It enables nurses to check among others the decubitus position, whether the patient is out of bed, and even if the patient has passed away. According to Momo Medical, the only feature lacking is the monitoring of human incontinence. The finished project will be able to detect solid stools and hence, when integrated into the BedSense system, greatly assist the nurses.

The aim of the project is to develop a non-intrusive device that can be integrated in the BedSense system and can detect solid stools. The device should be easy for nurses to use and not burden them with extra work. To accomplish this product, the project is split up into two parts: Hardware and Software. An overview of the project is given in Fig. 1.1. In general, the following workflow characterizes the project: The sensor detects gasses of the solid stools and translates this into an electrical output signal. In order to test the sensor, simulation with gasses has been done. The sensor read-out values have been used to train a detection algorithm. Both the output values and the outcome of the algorithm are transported via a wireless communication to the server. This report details the hardware development, meaning the sensor, simulation with gasses and the sensor read-out.

The report is divided into multiple parts. First, the project description discussed in Section 1.1. The functional requirements are elaborated upon in Chapter 2. Secondly, the way of detecting solid stools is explained in chapter 3. After, the sensor selection, validation and calibration is discussed in chapter 4. Thirdly, the design is discussed in chapter 5. This chapter contains the description of the different prototypes and detailed explanations regarding the design choices made. Chapter 6 summarizes the work done by the software group. Finally, chapter 7 describes the implementation and testing of the final design. The report ends with a conclusion and future work in chapter 8.

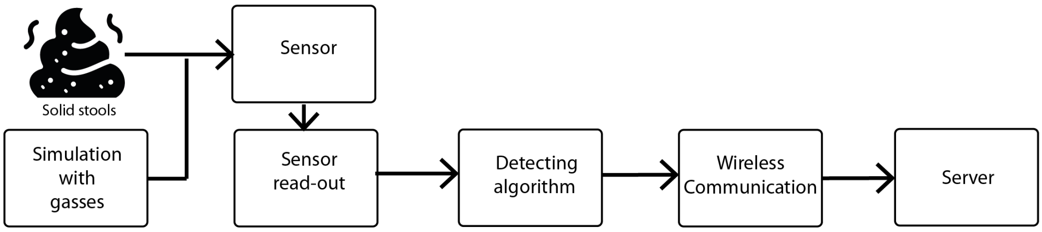

Figure 1.1: The flowchart of the project.

1.1. Task description

This section gives background information on the project topic. It describes the problem and defines the scope of the project. Besides, it argues why a system, solving this problem, is needed.

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[1] https://www.momomedical.com/

The project was proposed and defined by Momo Medical, a small TU Delft-based company that develops the BedSense. The BedSense monitors the patients behaviour in nursing homes. While implementing the BedSense in nursing homes, nurses explicitly asked for a device capable of detecting solid stools. This paved the way for this project.

At this moment, nurses check whether patients have defecated at regular times during day and night. Checking the defecates is done by smelling or by checking the diaper. This intrusive way of checking defecates, takes a lot of time for the nurses. In addition, it disturbs the sleep or rest of patients. Finally, due to checks on certain times, it could take a while before the diaper has been changed. For example, if someone defecates right after the nurse checked the patient. Solid stools have low pH values. Therefore, it damages the skin if the diaper is worn too long. Irritated skin and rash is a common problem for patients.

The aim of the project is to detect solid stools. 'Solid' is added on purpose. As skin damage due to urine does not occur frequently, it is not required to detect urine. Besides, liquids are absorbed much better by a diaper than solid stools. Meaning that the scope of the project is purely detecting solid stools.

Making a system of being able to detect solid stools, has the following benefits: First of all, it lowers the workload of the nurse. Due to a detection system, the routine checks along the patients are no longer needed, which significantly saves time. In addition, disturbing patients in their sleep or rest is avoided. Finally, the system will monitor 24/7. Since the nurses get notified when a patient has defecated, it reduces the total time a patients has to wear a full diaper. This lowers the risk of irritated skin and rash by the patients.

In order to make a product useful for the end-users, it is important to take the characteristics of the stakeholders into account while finding a solution. The nurses will be the final end-users. They use the notification side in order to work more efficiently. For this kind of end-users it is important to make the product as easy-to-use and user-friendly as possible. Their main focus is taking care for the patients. Mainly, they are not technically skilled and the aim of the system is reducing workload, not making it more complex.

Another group of stakeholders are the patients in nursing homes. One specific subgroup are the patients suffering from dementia. As these patients can show strange behaviour regarding unfamiliar objects. The device should be a robust product unit. In addition, having equipment directly attached to the patient, is not recommended. Since patients could take off the medical equipment.

2

Requirements

This chapter presents the functional and design requirements. They provide guidelines during the process of selecting a detection system and hardware components.

Functional requirements

Table 2.1, shows the functional requirements. Every requirement has its unique reference, which is be used throughout the document. In addition, the requirements are explained shortly.

Table 2.1: The functional requirements.

Reference	Requirement	Explanation
FR-01	The system should detect solid stools.	This is the main goal set by Momo Medical.
FR-02	The system should detect solid stools in a nursing home's room.	This means that the system should work under different conditions like: an open window, parfum, eating meals, etc.
FR-03	The system should be made as simple as possible.	The more complex, the easier it is to make mistakes in the development process and the harder it is to fix bugs.
FR-04	The system should be made as energy efficient as possible.	Since each nursing home's room would need such a system, energy-consuming units would cause a significant increase of the overall energy consumption of a nursing home.
FR-05	The system should not react on urine.	Since urine is less irritating for the skin, there is no need to detect it.
FR-06	The system should not damage the nursing home's room in any case.	This means that measures needs to be taken in order to prevent fire, explosions, outages of the electricity grid, etc.
FR-07	The system should be low-cost. The final unit should cost approximately €30,-.	This cost-requirement is set by Momo Medical.
FR-08	The system should send its data to the server via WiFi.	This requirement is set by Momo Medical.
FR-09	The system should be plug-and-play. The system should only be powered for operation.	For nurses it is important to have a system which can easily be installed.
FR-10	The system should have a lifetime of 2 years before replacement.	This time span is set by Momo Medical.
FR-11	The system should not raise privacy invasive feelings by the patient.	This means that monitoring with for example camera's is not a way to go.
FR-12	The system should fit in a box of 15 by 15 cm.	In this way it is easy to place somewhere in the nursing home's room.
FR-13	The system should not hurt the patient in any case.	The system should for example not cause the patient being electrocuted or burned.

FR-14	The system should detect solid stools from a distance of 50cm.	Since patients with dementia pull off all kind of sensors from their body, while even harming themselves, it is not allowed to use equipment directly attached to the patients body. 50cm is the minimal distance set so products could be attached to the side of the bed.
FR-15	The systems product unit should be made as user-friendly as possible.	It is assumed that nurses are not technically skilled.

Design requirements

The requirements presented above are mainly used to select the best way of detecting solid stools (See Chapter 3). Furthermore, based on these requirements gas sensors have been selected (See Chapter 4.1). The requirements presented in this section are the design requirements. They are mostly used for the printed circuit board (PCB) and case design discussed in Chapter 5. Table 2.2 shows the design requirements. Each requirement is listed with some explanation. In addition, every requirement has its unique reference, which will be used throughout the report.

Table 2.2: Design requirements.

Reference	Requirement	Explanation
DR-01	The module contains multiple slots for the gas sensors.	The gas sensors will give the needed data for the algorithm. Using multiple sensors can increase the reliability.
DR-02	The module contains a microcontroller which is able to perform the necessary computations.	On-board processing is preferred in order to be less dependent on external hardware.
DR-03	The module contains a microcontroller which is able to connect to WiFi.	This is a requirement set by Momo Medical.
DR-04	The module contains a slot for the DHT22 humidity and temperature sensor.	The temperature and humidity are measured separately in order to compensate for it.
DR-05	The module needs to be powered by a 5vDC source.	The gas sensors are working on 5vDC.
DR-06	The module needs to be protected against reverse polarity.	It could happen that different adapters are plugged-in accidentally, this should not cause severe damage to the module.
DR-07	The module needs to be protected against short circuits.	This will prevent the module from being damaged severely if a short circuit occurs.
DR-08	The module should be waterproof.	There is a chance that someone for example spills some water over the module, this should not cause malfunctioning of the module.
DR-09	The module should not have sharp edges or hot faces which could hurt the patient.	This will prevent the patient from being hurt by the module.
DR-10	The module should be mechanically robust. The size of the case should be 5mm thick. No weak components should be placed on the outside of the case.	Patients with dementia generally do not handle unfamiliar devices with care.

DR-11	The gas sensors should be easily replaceable.	Since the sensors have a limited lifetime, there should be a possibility in order to replace them.
DR-12	The device should be easy to assemble.	This will speed up the assembling process, thus making the price per unit lower.
DR-13	The module should be maintenance free.	Once the module is placed in a nursing home's room, it is not preferred that maintenance is needed during its lifetime.
DR-14	The module should be easy to place in a nursing home's room. No additional hardware should be needed.	It is preferred to have one module with a power cable, so there is no need for changes within the room or additional hardware in order to operate the module.
DR-15	The module should discriminate between solid stools and other events when gasses are emitted.	If cleaning, eating a meal or other events occur, the module should not raise an alarm.
DR-16	The module should notify the user if essential hardware like sensors are broken.	This is needed in order to prevent the situation that invalid data is used for detecting solid stools.
DR-17	The sensor output values should be stable and reliable, during the life-time of the system.	These conditions for the output signals are needed in order to have valid data for the algorithm.
DR-18	There should be visible feedback so the user knows the device is properly powered.	This will avoid the case that a broken adapter is used during installation.

3

Solid stools detection

This chapter answers the question: "How can solid stool be detected?". There are different methods to detect solid stools. In this chapter they are shortly introduced. The chapter is concluded with a decision for one of these methods.

A common problem of elderly people is incontinence-associated dermatitis or diaper rash. This is caused by prolonged exposure to the moisture of stools and urine combined with changes in pH and the presence of ammonia [1]. Detecting moisture can be used to validate whether solid stool is present. Other detecting methods are direct sensing of the bowel movement by means of ultrasound or sensing the surrounding air for certain gasses emitted by the bowel movement. Hence this chapter elaborates on three possibilities: detecting moisture, ultrasonic sound and measuring gas.

3.1. Moisture

Moisture affects conductivity and hence can be used to detect urine and feces. Simik, Chi and Wei developed a low-cost diaper insert that detects urine from 2 mL and stools from 90 grams with a cost of 20 to 30 eurocents per insert [2]. This insert contains two metal strips covered and separated by a medical gaze. When the medical gaze becomes wet, the conductivity between the two wires increases. This technique only could be used to detect stools as the insert lies on top of the diaper. The urine will be absorbed into the diaper, unlike the bulk of moisture of the feces.

Another method of moisture detection is using high-frequency radio frequency (HF-RF). The detection could be done in combination with hydrogel (e.g. [3]) or an insert (e.g. [4]). The principle behind the HF-RF-detector is a L-C network formed by two coils and a plate - separated by an substrate - changing its resonance frequency when the substrate becomes wet [5]. However, differentiating between urine and feces is difficult. The substrate can act as an diaper and retains the moisture of urine as well as the moisture of feces.

3.2. Ultrasonic

Ultrasound or ultrasonic sound has a high frequency (typically 2 to 18 MHz). In contrast with radar, it uses sound waves instead of electromagnetic waves. When an ultrasonic probe with a speaker is placed against the body, parts of the body reflect the audio wave back to the probe. From the delay of the received audio wave, information of what is under the skin can be extracted. Also the intensity and other factors play a role.

In the medical setting, transabdominal ultrasound is often used as a first-line tool to detect various digestives diseases [6]. It allows medical professionals to examine the dilation of the scanned intestines. This technique is also used specifically on the rectum dilatation of healthy and unhealthy people. As there is a relation between defecation and the change in rectal diameter [7]. Hence, it might be possible that an ultrasonic sensor may predict whether a patient will pass a bowel movement. This method is currently in the process of being patented [8]. A Japanese company is implementing this technique, which adds to the feasibility to use this method to detect bowel movements. For now, this technique is not implementable.
The nature of ultrasonic imaging requires the ultrasonic sensor to be directly on the skin itself. In addition it should be located relatively precisely in order to detect the rectum size. Hence, the use of such sensor would be labour intensive and have a relatively high variable cost per unit.

3.3. Gasses

Finally, another way of detecting solid stools is measuring the released gasses. Gasses have many properties that can be measured, hence there are many different types of sensors based around different properties of the gasses. The sensor is meant to convert the chemical information of the gas into an electrical signal, which could be either a frequency, current or voltage signal[9]. A 2014 review of gas sensors identifies six categories of sensors: catalytic, electrochemical, optical, semiconductor, thermal conductive and acoustic wave gas sensors [9], each having their own advantages and disadvantages (See chapter 4.1). The main benefit of a gas sensor over the moisture or ultrasonic sensor is that it is not labour intensive and does not have any associated variable cost.

Conclusion

To decide the best method for detecting solid stools. Functional requirements of the methods have been compared in Table 3.1.

The meaning of the symbols is as follows:

- + does comply
- -+ partly complies
- - does not comply

Table 3.1: Functional requirements comparison for the three possibilities.

	Moisture	Ultrasonic	Gasses
The system should be as simple as possible for the user [FR-16].	-+	-	-+
Differentiation between urine and solid stools [FR-05].	-+	+	+
The unit prize should be low [FR-07].	+	-+	-+
The system should be safe for the patient [FR-13].	+	+	+
Detection should happen from a distance [FR-14].	-	-	+

The essential requirements listed in chapter 2 are used to find the best method for detecting solid stools. Since no devices should be attached to the body of the patient[FR-14], using ultrasound method is not possible. Furthermore, the moisture inserts needs to be changed while changing the diaper, increasing the workload and variable costs[FR-16]. Finally, the disadvantage of using HF-RF is the differentiation between urine and solid stool[FR-05]. Therefore, the method which could comply to all the described requirements seems to be gas sensing. The development of using gas sensors to detect solid stools is being further discussed in the upcoming chapters.

4

Sensors

4.1. Gas sensors

This chapter describes the process of selecting the type of gas sensors used in the project. In addition, the validation and calibration of the sensors are described.

In Section 3.3 of Chapter 3 it has been decided to use gas sensors for detecting solid stools. Before selecting the type of gas sensors, it is crucial to know which gasses have to be detected.
The gasses released when someone defecates can be seen in Table 4.1. The gasses N_2, H_2O, CO_2, H_2, and CH_4 do not have any odor, and thus do not make the solid stool smell bad[10]. However, the traces of H_2S in the air, result in a heavy odor at restrooms.

Table 4.1: Gas composition of human organic waste [11].

Substance	Symbol	Percentage [%]
Methane	CH_4	50 - 70
Carbondioxide	CO_2	30 - 40
Hydrogen	H_2	5 - 10
Nitrogen	N_2	1 - 2
Water Vapour	H_2O	0.3
Hydrogen Sulphide	H_2S	traces

The main unique gasses released from human organic waste are CH4 and H2S [12] [13]. H2S gives the human organic waste its particular smell, however its concentration is relatively low (around 0.1-0.01 ppm). The concentration of CH4 is in the order of 50ppm-100ppm. To detect gasses with a gas sensor a concentration higher than the lower ppm limit[1] of the sensor needs to be present. Commercially available sensors have ranges from a lower ppm limit of 50ppm to several hundreds of thousands of ppm as the upper ppm limit. Therefore, it is difficult to detect gasses like H2S, since these traces have concentrations far below 50ppm. Research has been done on making specific sensors for detecting H2S, also at low concentrations (0.1ppm) [14]. However, these academic sensors are not commercially available yet. Therefore, the focus during this project is on detecting CH4 concentrations, since this gas will be released the most, while defecating.

Type of gas sensors

In Section 3.3 it is mentioned that there are several types of gas sensors available on the market. The detailed working principle of these different types of sensors can be found in Appendix D.

Each gas sensor category has different characteristics summarised in Table 4.2. In this table advantages and disadvantages of the six sensor types are shown. In addition, for each type, a reference to an industrial example is given.

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[1] This is the lowest concentration of a gas the sensor can detect.

Table 4.2: The advantages and disadvantages of six sensor types for detecting feces.

Sensor-type	Advantages	Disadvantages	Example
Semi-conductor	- Low price per unit - High sensitivty - Long lifetime - Can function properly for up to 10 years	- Low selectivity - High power consumption in some cases	[15]
Thermal conductivity		- Moderate cost per sensor of 150 euros - Low selectivity - Operating on higher temperatures of 100+ degrees Celsius	[16]
Catalytic	- Moderate selectivity, cannot differentiate combustible gasses - Low cost per sensor of 30 euros	- Low sensitivity - Lower limit of 500 ppm methane	[17]
Electro chemical	- High sensitivty	- Moderate cost per sensor of 130 euros	[18]
Optical	- High selectivity but cannot differentiate hydrocarbons - High sensitivity - Lower limit of 30 ppm methane	- Moderate cost per sensor of 200 euros	[19]
Acoustic wave		- Cannot be bought separately - Very high cost per device starting from 5000 euros - Not compact nor portable	[20]

Gas sensor selection

One important trade-off in selecting gas sensors is the selectivity versus price. The selectivity of a sensor specifies to which degree a sensor can distinguish one gas from another gas. Ideally, sensors with high selectivity detect only the gas they are made for. In reality, cheaper gas sensors are cross-sensitive for other gasses, meaning that they are also triggered by other gasses. Furthermore, another important feature is the sensitivity of a sensor. The sensitivity of a sensor is an indicator for the magnitude of output as a response to a certain gas. The better the sensitivity, the lower the concentration of the gas can be.

Table 4.3 shows the requirements used for selecting the type of gas sensor. The meaning of the symbols is as follows:

- + does comply
- -+ partly complies
- - does not comply

Since not all the properties of each type of sensor are known, some boxes are left empty. Besides the functional and design requirements, two additional practical requirements regarding the delivery and availability of the sensor type have been added. The three types of gas sensors available were semiconductor-based gas sensors, electro-chemical-based gas sensors and optical-based gas sensors. However, the optical-based gas sensors are expensive (See Table 4.2). Since the lifetime of electro-chemical-based gas sensors is not well-known it is difficult to decide on this feature.
Although the selectivity of electro-chemical-based gas sensors needs to be moderate (See Table 4.2) the sensors which are being sold at local suppliers have approximately the same selectivity as the semiconductor-based sensors. Therefore, the cheapest sensors have been selected, being the semiconductor-based gas sensors.

The selectivity of these cheap gas sensors is most of the times low. In order to compensate the lacking selectivity, the decision was made to use multiple cheap semiconductor sensors designed for different gasses.

Table 4.3: Requirements comparison for the six different sensor types.

	Semi-conductor	Thermal conductivity	Catalytic	Electro-chemical	Optical	Acoustic wave
The system should be as energy efficient as possible [FR-04].	-					
The sensor module should be as cheap as possible [FR-07].	+	-	+	-	-	-
The system should have a lifetime of 2 years [FR-10].	+					
The sensor should be selective [DR-15].	-	-	-	-+	+	
The sensor should be readily available.	+	-	-	+	+	-
Delivery should be within one week.	+	-	-	+	+	-
The sensor should be easy to use (Testing and integration should be done in one week.) [FR-03] [DR-12].	+	+	+	+	+	-

Each sensor gives a different response to a certain gas concentration, hence the combined information will provide a fingerprint of the gas composition in the air.

A well-known and often used series of semiconductor gas sensors is the MQ-series[2]. Different MQ gas sensors[21] were bought. These sensors have been used in the continuation of the project.

The working principle

The MQ-gas sensors are Metal Oxide Semiconductor (MOS) gas sensors (See appendix D for more information). Within the sensor, a reaction with the target gas changes the oxide surface. This change of the oxide surface, causes a change in electric resistance. The MQ sensor output is combined in series with a 10 $k\Omega$ resistor referenced to ground. This resistor results in a voltage divider. Therefore, the output voltage is sensitive to the sensors resistance, and thus indirectly to the concentration of gas.

In order to optimize the reaction with the target gas, heaters are placed inside the sensor. These heaters, after some heating time, take care for an stable temperature within the sensor. The temperature has a discriminating function, since the reaction temperature is not the same for all gasses. Therefore, the temperature within a gas sensor makes reactions with certain gasses possible, while other gasses do not react at that temperature.

Besides temperature, the humidity does also influence the sensor output. Since these two variables influence the sensor output, it was decided to add an additional DHT22 temperature and humidity sensor next to the gas sensors in order to compensate for these two variables.

4.2. Sensor validation

There are multiple MQ gas sensors available for detecting CH4. Therefore, it is important to select the sensors which are most sensitive to solid stools [FR-01]. Besides, the sensors should detect gasses from a distance of around 50cm [FR-14]. Therefore two questions regarding the selection of sensors arise: 'Can they detect a smell in an open room?' and 'Can they identify if a smell is fecal in origin?'. To answer these questions, two tests were performed.

First, the sensors were exposed to the air of a climate controlled environment to quantify the mean and variance of their responses (over multiple trials under the same conditions). Then, the sensors were set 50 cm away from a roughly 40 mL volume of hand sanitizer. The hand sanitizer was chosen as a likely source of

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[2] The letters MQ are related to the product name and are no abbreviation. The number mentioned after MQ determines the specific gas detection characteristics.

Table 4.4: MQ sensors, the gasses they are designed for to measure, and their sensitivity according to the experiments.

Sensor	Diaper	Sanitizer	Designed to detect
MQ-135	++		CO2, NH4, NOx, benzene, alcohol, smoke
MQ-3	++		alcohol
MQ-2	+		LPG, i-butane, propane, methane, alcohol, hydrogen
MQ-9	++		CO, methane, LPG
MQ-8			hydrogen
MQ-7			CO
MQ-6		+	LPG, butane, propane
MQ-5		+	LPG, natural gas
MQ-4	+	++	methane, natural gas

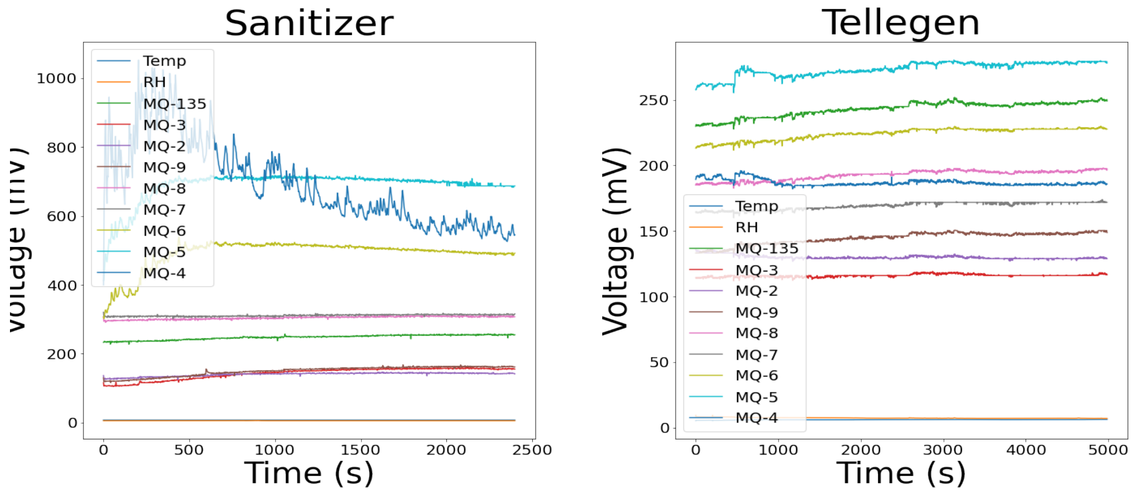
interference for the real-world application, as it is commonly used in nursing homes and generates a distinct smell.

The output voltage from the sensors during this test is shown as a function of time in Fig. 4.1b and Fig. 4.1a. The MQ-4, MQ-5 and MQ-6 sensors clearly responded to the presence of the hand sanitizer, while other sensors barely did. This shows that the sensors are able to detect a small amount of fumes from a compound releasing gas. The signal strengthens and decays over time, the decay is expected to occur because of the gas diffusing out into the room (See Appendix D for information about gas diffusion).

Next, the sensors were put in a 10L container with a soiled baby diaper. Since at this moment of the project it was easier to get a baby diaper than a diaper from nursing homes patients, a baby diaper has been used. The diaper was collected the night before the experiment and kept in a sealed zip-lock bag. As the experiment took place at 9 A.M., the fecal matter was likely 6-12 hours old at that time. The setup was put in a closed container this time, to avoid having the foul smell spread around the lab.

The voltage output from every sensor is shown in Fig. 4.2. The MQ-2, MQ-3, MQ-4, MQ-9, and MQ-135 sensors showed a steady increase in output voltage. No decay in voltage was determined. As the volume was closed, there was no way for the gas to diffuse, explaining the lack of decay. The sensor responses were less pronounced compared to the experiment with hand sanitizer. This is assumed to have two causes. First, the stool was at least 6 hours old before the experiment started. It is possible that a lot of gas had already escaped. Second, the stool might release gas at a slower rate. This is hypothesized because, unlike the hand sanitizer, the stool does not completely vanish into the air. Nevertheless, this result, when compared with the data from the hand sanitizer, shows that using multiple sensors is a valid way of differentiating between two compounds.

The results from these experiments are provided in Table 4.4. This table provides and overview of what each sensor is designed for and how sensitive it is to each substance. The MQ-3 sensor is designed to sense only alcohol, but seems to work at detecting the diaper also. This is assumed to be due to cross-sensitivity, as the diaper did not contain any alcohol wipes or any other alcohol-related product. The datasheet confirms that the sensor should be slightly sensitive to methane, which makes this a plausible theory. [21]
Based on these results MQ-3, MQ-5 and MQ-135 were selected as useful gas sensors for detecting solid stools. However, finally MQ-135 has not been used for the algorithm due to the noisy output signal [22].



(a) Response of the ensemble of sensors with a small volume of hand-sanitizer present.

(b) Response of the ensemble of sensors in a lab without any compound.

Figure 4.1: Responses of sensors in different environments.

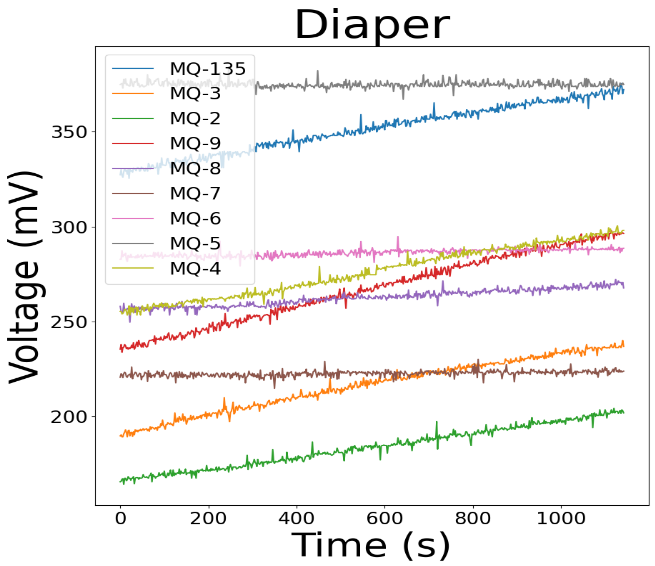


Figure 4.2: Response of the ensemble of sensors in a closed contained with a dirty diaper.

Modeling noise from humidity and temperature

The last experiment showed some modulation from the fecal matter in the sensor signal. However, the signal strength was about 50 mV over the span of 10 minutes. This can be seen in Fig. 4.2. Sources of noise could overshadow this signal.

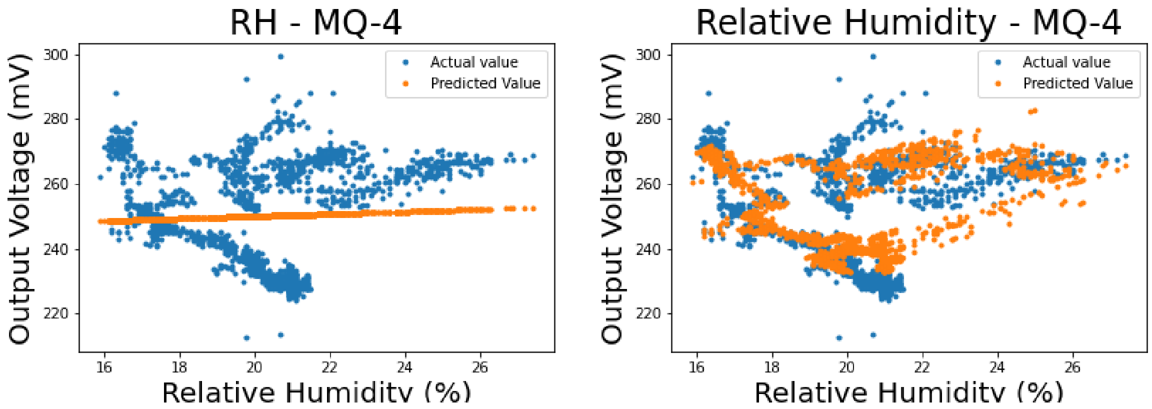
In this section, a method to model noise from humidity and temperature fluctuations is presented. A separate temperature and humidity sensor can measure these physical quantities and with that information, the noise can be reduced. The noise is reduced by estimating its instantaneous value from the model and taking the difference between the signal and the estimated noise.

Two models were fitted: first, a combination of two linear models, and second, a single bilinear model. The linear model estimates the contribution of each noise source - temperature and relative humidity - separately and then combines the estimates to form an instantaneous noise estimate. The results of a linear least-squares fits for one sensor is shown in Fig. 4.3a. The fit is not very accurate, the scatter plot shows that the data is not highly correlated.

To find a better estimate, a bilinear model was considered. In this model, the least-squares fit is two-dimensional. Instead of fitting a line to a single input, a plane is fitted to two inputs. In this case, the two inputs are the temperature and humidity. The result of this fit is shown in Fig. B.2. This fit looks much better.

The data is somewhat hard to visualize, since two variables simultaneously influence the output. It might seem like the signal is showing some hysteresis, as seemingly two outputs are provided for the same input. However, this is not the case. It is due to the fact that even if the relative humidity for example is fixed, temperature can still change and influence the output of the sensor. In this dataset, the relative humidity was the same at two points in time, but the temperature was different. Hence, there are two outputs for the same input. The bilinear model accounts for both sources of noise, but the linear one does not. That is why the bilinear model follows the curve better.

In conclusion, a bilinear fit can accurately estimate the signal from most MQ gas sensors due to temperature and humidity fluctuations and thereby remove them. The figures of all sensors are available in appendix B.



(a) A linear fit to relative humidity.

(b) A bilinear fit to both relative humidity and temperature.

Figure 4.3: Two ways of modeling the noise from temperature and humidity

4.3. Sensor calibration

The DHT22 sensor is used to measure ambient temperature and humidity in the vicinity of the gas sensors. As described in section 4.2 these outputs can be used in order to predict noise on the sensor outputs. Therefore, the outputs of the DHT22 sensors needs to be accurate. During operations it became clear that the outputs of the DHT22 for the humidity was different from sensor to sensor. Therefore, it was decided to calibrate these DHT22 sensors for their humidity output. The method used for calibration is based on saturated salt solutions [23].

There are multiple reasons why these DHT22 sensors have been calibrated. First of all, it is important to make sure the readings of all the sensors are consistent with each other. Besides, accurate humidity outputs are needed for trying to predict sensor noise, see section 4.2. Finally, calibrating these sensors on humidity was doable within the scope of this project. The aim was also to calibrate the gas sensors, so calibrating these DHT22 sensors would give insights and skills, which could be used for the gas sensor calibration. Unfortunately, executing this gas sensor calibration was not possible, but an approach will be presented in section 4.3.

Theory

In order to understand the experiment some theory is presented. Humidity is the concentration of water vapor in the air. The DHT22 sensor, however detects the relative humidity. Relative humidity (RH), is the ratio between the 'external' partial pressure of the water vapour in the air and the 'internal' pressure of the vapour dispersed inside the liquid water[24]. Salt dissolved in water will change the internal pressure, and therefore change the relative humidity.

$$RH = 100\frac{p_w}{p_{wl}} \tag{4.1}$$

Saturated salt solutions create an environment with predefined partial pressures. This means that the relative humidity in such an environment is fixed. The relative humidities of multiple saturated salt solutions are given in the paper of Greenspan [23]. Making such a solution and placing a sensor inside this environment for a long period of time, will give the difference between the sensor output value and the fixed relative humidity known for that particular salt solution. The larger the surface between the salt solution and the air, the faster the relative humidity will stabilize to the predefined number.

Materials

The practical setup consists of an Erlenmeyer flask[3], a cylinder, a weight scale, a spatula, a balloon and the PCB. The chemicals used are distilled water, Sodium, Potassium, Lithium and magnesium.

The experiment

For this experiment four different salts and four different DHT22 sensors have been used. The four salts are selected, based on their ability to buy them in local stores and their spread fixed humidity levels. Two sensors have been placed in all the environments and two of the sensors have been placed in two of the environments. The steps to execute the experiment are listed below:

1. 5 mL of water is added to the Erlenmeyer.
2. For each salt, two times as much salt is added to the distilled water, then needed for the solubility concentration.
3. The salt is being mixed with the distilled water by shaking the Erlenmeyer in a circular movement.
4. The sensor is put into the Erlenmeyer and is enclosed using a balloon.
5. The solutions is left for rest, and the data is being gathered on a PC for approximately 90 minutes.
6. When the data of the humidity is swinging around the same value for an extended period (in this case 30 minutes), the measurement has been come to an end, since the humidity level has been reached.

Results

The four different salt solutions and their results are presented in this section.

The first reaction have been gotten by adding potassium to distilled water. The solubility of sodium in water is approximately 31% at room temperature, hence 310 g/L [25]. Therefore, 3.1 gram of Sodium is added to the 5 mL of distilled water in the Erlenmeyer. The relative humidity outputs of different DHT22 sensors placed in this saturated salt solution environment have been plotted in Fig. 4.4.

For magnesium the solubility is 550 g/L, therefore 5.5 grams of salt is used for 5 mL of distilled water. The resulting figure can be found in Appendix C.1a.

For sodium the solubility is 260 g/L, therefore 2.6 grams of salt is used for 5 mL of distilled water[25]. The resulting figure can be found in Appendix C.1b.

For Lithium the solubility is 840 g/L, therefore 8.4 grams of salt is used for 5 mL of distilled water. The resulting figure can be found in Appendix C.1c. However, the relative humidity outputs of the sensors placed in this particular saturated salt solution did not seem to go to the equilibrium relative humidity reference. Instead the relative humidity outputs did still drop after 2 hours of sensing. Since this would take too long anyway for a company to calibrate the sensors by using this saturated salt solution, it is advised to not use this salt.

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[3] An Erlenmeyer flask is used in order to optimize the surface between the salt solution and the air, while having a minimal output gap.

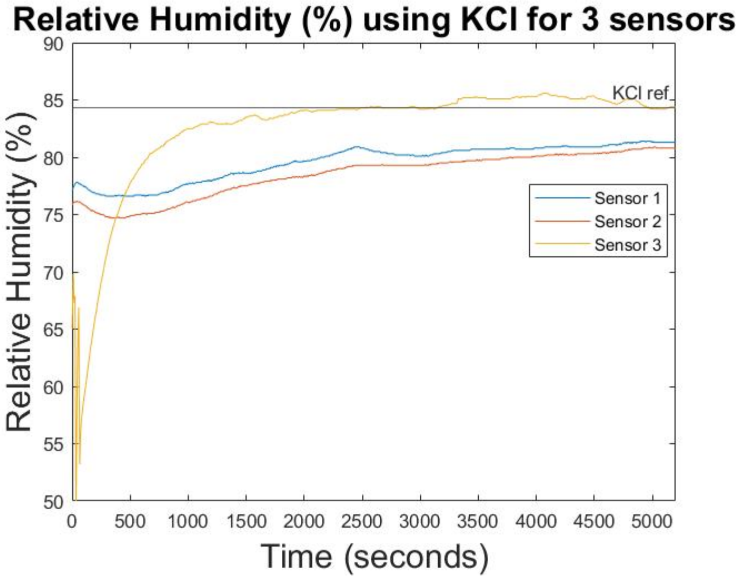

Figure 4.4: Relative humidity of a KCL solution for different DHT sensors.

Table 4.5: The error between the measured value and the reference value for each sensor per salt solution.

		Sensor 1		**Sensor 2**		**Sensor 3**		**Sensor 4 (blanco)**	
	Reference	**Measure**	**ERR**	**Measure**	**ERR**	**Measure**	**ERR**	**Measure**	**ERR**
MgCl	32.78	36.29	3.51	35.92	3.14	-	-	-	-
NaCl	75.29	73.67	-1.62	73.77	-1.52	-	-	74.63	-0.66
LiCl	11.3	18.32	7.02	19.41	8.11	17.29	5.99	18.92	7.62
KCl	84.34	81.34	-3	80.98	-3.36	84.81	0.47	-	-
RMSE			**4.3**		**4.7**		**3.0**		**3.8**

Error correction

After measuring the relative humidities in the different environments, two linear regression models for both sensor 1 and 2, were made based on the reference value and the measured value. It has not been done for sensor 3 and 4, since these sensors have only two measurements. The models can be found in the Appendices C.2a, C.2b, C.3a, C.3b. An overview of the error between the reference relative humidity in a specific environment and the measured relative humidity in that environment can be seen in Table 4.5. In addition, the Root Mean Square Error (RMSE) per sensor is given. It is clearly seen that the error in the LiCl environment is substantial larger than the errors in the other environments. This is probably due to the fact the relative humidity in that environment was not yet on its predefined value within 2 hours. Therefore, leaving out this value, the overall error per environment for sensor 1 and 2 are not exceeding +/- 4. On a scale of 100, this is 4%. In addition, using a linear regression model, which has been applied for sensor 1 and 2, could be a good way of calibration, since the RMSE <1 if the LiCl measurement is excluded. Since the error is small, calibration of the DHT22 sensors is not essential. However, using a linear regression model could a good option.

Gas Sensors

As mentioned priorly, the initial idea was, calibrating the gas sensors after calibrating the DHT22 sensors. However, in practise calibrating gas sensors is much more difficult than calibrating DHT22 sensors. Not only the equipment used is very expensive, but also the expertise needed to extract viable data from the measurements is very difficult. Equipment needed for calibrating these sensors would be ideally a gas analyser[4].

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[4] A gas analyser detects the gasses in a gas mixture and defines their concentrations in ppm or ppb

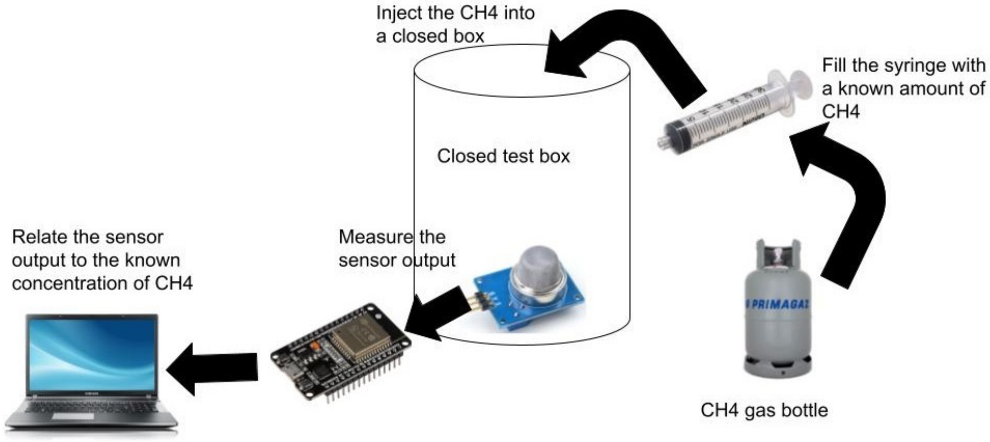


Figure 4.5: The test setup for gas sensor calibration.

By adding an sensor in the gas flow, the output of the sensor could be related to gas concentrations at the ppm or ppb level. This gives a better characterization of the sensors. A relation between concentration change and output change could be established and a lower ppm level for gasses could be determined for a gas sensor.

To avoid the expensive equipment, another and more easy way of calibrating the gas sensors is presented in Fig. 4.5. It consists of a gas bottle, and a crane, which could let in small doses of another gas. First, the gas bottle will be filled with nitrogen, afterwards a small controllable doses methane or another usable is being added to the already existing gas in the gas bottle. To control the doses of gas injected in the gas bottle an syringe will be used with a known volume (See Fig. 4.5). Since the amount of gas in the bottle is known and the volume of the bottle is known, the ppm value can be calculated. In this way the calibration of the gas sensors can be executed.

However, getting a gas bottle of CH4, needed for this calibration, was not easy. Due to safety restrictions it was not possible to get the needed gas within the time-frame of this project. Therefore, this approach is only presented.

5

Implementation

In this chapter the implementation will be discussed in detail. Since during the project multiple implementations have been made, each one will be discussed separately. Furthermore, the electrical implementations, topics like the case design, noise and reliability will be elaborated upon.

As described in Chapter 4 some MQ gas sensors were selected in order to detect solid stools. In addition, the decision was made to place an additional DHT22 sensor in the vicinity of these gas sensors. For these sensors a production unit has been developed. The first implementations were mainly meant for gathering data. That is making a practical design, which could be placed at different spots in order to gather data. The final implementation is meant to be placed in a nursing home's room.

This chapter focuses on the design process of these implementations. During the project four different PCB implementations have been designed and tested. In addition a case has been designed in order to cover the PCB and electrical components. Finally, other discussed topics are the power supply, the microcontroller, noise and reliability.

5.1. Power management

The power supply is of utmost importance in order to let the device work in an appropriate way. There are several ways in order to deliver enough power to the design. Some possible solutions are listed below.

- Using a battery and a charger.
- Using a power plug with a wire and doing the AC to DC conversion within an adapter close to the socket.
- Using a power plug with a wire and doing the AC to DC conversion within the product some distance away from the socket.
- Integrate the product within a power plug, so there is no need for a wire.

Using a battery and a charger is most useful in cases were a power wire cannot be implemented. In the scope of this project a power wire is no problem. A lot more devices within the nursing home's room have cables which are manged in such a way that they are no obstacles for the patients and the nurses.

Using a power plug with a wire could be a possible implementation in this project. However, there are two possible ways of transporting the power to the product. In the first case the voltage of the grid is transformed into a low voltage suited for the product. This is done in an adapter close to the socket. In this way the power management can not be integrated in the final product and the compactness is thus less. There are two different components: the product itself and a power adapter. On the other hand advantages of this approach are the safety and the modularity. First of all, the voltage over the cable is lower than the grid voltage from the socket, due to the conversion at the beginning of the cable. A cable carrying a lower voltage is always safer for the patient, than a cable carrying the grid voltage. The other advantage is the modularity. In case the power adapter is broken. It is easy to replace this adapter without the need to replace the whole product, which could be the case if the power management and the product are integrated into one product.

In the second case the transformation is done within the product. The design will be more compact, however it is less safer due to the higher voltage along the cable. In addition the modularity is reduced, because the product should be opened if there is a failure in the power management system.

One other option left is the integration of the product within a power plug. Detecting the gasses of solid stools is more reliable in the near proximity of the solid stool. Since this implementation has no wire, the places of the power sockets in the room decide whether the device could be placed close enough to the patient. This way of dependence is undesirable, since influencing the places of the power sockets could only be done by power extension cords. Using these cords would finally give the same result as making a product with an integrated power management system.

Therefore, it has been decided that a power adapter will be used. This is safer, gives more flexibility in placing the product and it is easier to replace a broken adapter.

Expected power consumption

For selecting the right adapter an estimation of the expected power is needed. The two kind of components consuming the major part of the power will be the microcontroller and the gas sensors. For both components an estimation of the power consumption will be made.

- The TTGO ESP32 (see Section 5.2) has a working current of 67mA and a working voltage of 5V. The power consumed is thus 0.3W.
- Assuming that the sensors need a startup peak power for heating of 0.7W each.
- As 6 sensors will be used in the final design, see Section 5.6, the peak power consumption will be 4.2W.
- A margin of 0.5W will be used.

Taking the considerations above into account, the total peak power will be 5W.

As explained in Section 5.2, a TTGO ESP32 will be used in the product. The TTGO ESP32 can be powered via a USB connection, which delivers 5V and 1A. One way of powering the gas sensors is via the 5v output pins of the TTGO ESP32. Because the 5v output pins are directly physically connected to the input pins of the USB, the maximal power output is the maximal input power minus the power needed for the TTGO itself. The power consumed by the TTGO itself in working conditions is about 0.3W. Therefore the maximum power delivery by the 5v output pins of the TTGO is 4.7W. This way of powering is used in the second implementation, see Section 5.4.

However, as can be read in Section 5.6 the final implementation uses 6 gas sensors. Powering can than be better done, directly from the input DC-jack to the gas sensors and not via the ESP32.

The DHT-22 sensor needs 3.3VDC. Since there is a voltage regulator on the ESP32 board, this sensor could be powered from a 3.3VDC output pin of the ESP32. In the final design however, the 5VDC is converted by means of an LM1117T-3.3 [26] to 3.3VDC. In this design also a ESP32 Rover is used which is powered via an 3.3VDC input pin. Both the ESP32 Rover and the DHT-22 sensor are powered via the voltage regulator.

The adapter used for powering the PCB in the third and fourth implementation is the 5V adapter of Momo Medical. This adapter is rated at 5V and 1A, which is enough for our device. Besides, it has the European safety mark so the electronics inside are safe. Using a ready-to-use adapter, has been chosen to save time and focus on other more essential parts of the project.

5.2. Microcontroller

The microcontroller is the core of the system. It should be able to execute the necessary computations according to design requirement DR-03 and it should be able to send its data to the server according to functional requirement FR-08. This section will elaborate upon the decision making process for selecting the microcontroller of the system.

ESP32

The already existing product, the BedSense, does have an ESP32 [27] as the internal microcontroller. Therefore, a straightforward step was to first have a look into the option of using an ESP32. Some advantages and disadvantages are listed in Table 5.1.

Table 5.1: The advantages and disadvantages of using an ESP32 as a microcontroller.

Advantages	Disadvantages
Easy to implement Bluetooth communication.	Certain pins need to be unconnected/ pulled-up/pulled-down during Booting.
Easy to implement WiFi 2.4GHz communication.	Certain pins need to be unconnected while using the WiFi functionality. This limits the number of ADC pins.
Low power consumption.	Small memory 448Kb ROM and 520 Kb SRAM.
12-bit SAR ADC up to 18 channels.	
Additional interfaces like I2C, UART and SPI.	

As the communication between the BedSense and the server should be done via WiFi according to requirement FR-08, using an ESP32 in the design would certainly gain advantage on that aspect. Besides, the limited memory could be dealt with. In the worst case external memory could be added. Also the problem of limited number of ADC pins could be overcome by using a multiplexer.

On the other hand this microcontroller has a really low power consumption characterisation and it has a WiFi feature for transferring data to the server. Finally, the build-in ADC pins ease the work of converting the analog sensor values to digital values. No external ADC needs to be used.

Therefore, it was decided to use the ESP32. This microcontroller saves work and it is compatible with the BedSense module. At the start of this project a TTGO ESP32 [27] with a LCD screen has been used. The screen was used in order to print the sensor values and to give some visual feedback. In the final design a ESP32 WRover [28] has been used. This ESP32 can be SMD soldered on the PCB and more ADC pins can be used than a ESP32 on a breakout board, where some of these ports are not connected.

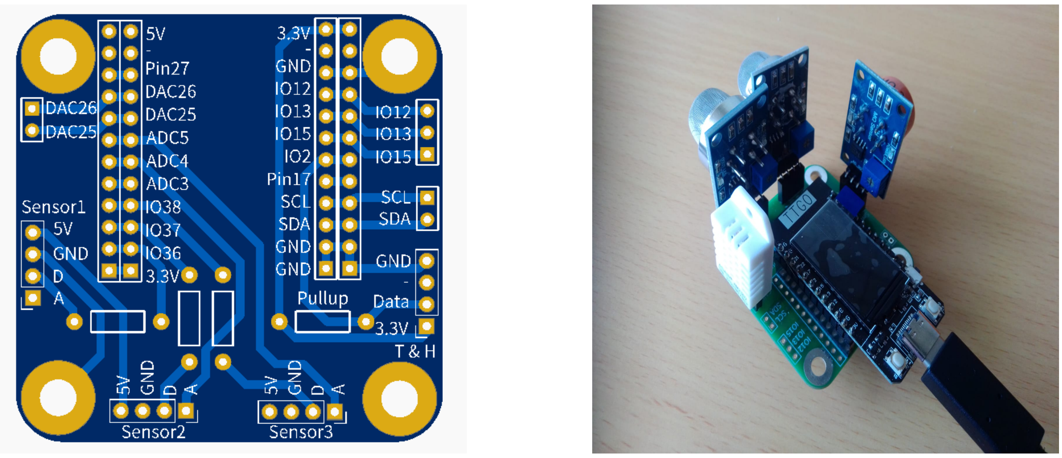
5.3. Implementation 1

The first implementation was a collection of 9 MQ sensor modules for detecting gasses and a DHT22 sensor for monitoring ambient temperature and humidity. These modules were inserted on a breadboard and wired to a TTGO ESP32. A breadboard was chosen as the aim of this prototype was to explore many possibilities and soldering components would make modifying the design harder.
Some possibilities that were attempted are powering the sensors from the ESP32, using less sensors, and routing many sensors through an analog multiplexer. The latter alternative was attempted to see if more sensors could be used than there are ADC channels on the ESP32.
This design was useful for characterising the sensors, but violates many design requirements like DR-07, DR-10, and DR-14. Therefore, PCB designs were developed (See Section 5.4).

5.4. Implementation 2

As described in Section 5.3 the first implementation was a breadboard prototype. This section will discuss the first PCB prototype which has been used in order to gather data with different sensors on board.

The main goal of making a PCB design at a early stage in the project was to distribute sensors boards among the team members and speed up the process of data gathering. Therefore, the design should be flexible and simple. The layout of this PCB can be found in Fig. 5.1a.



(a) A 2D view of the first version of the PCB design. **(b)** Assembly of the first PCB design (50mmx50mm) before encasing.

Figure 5.1: Figures of the first PCB design.

As can be seen in Fig. 5.1a the general layout consists of slots for 3 gas sensors, a slot for the DHT-22 sensor, a slot for the TTGO ESP32 and some additional connections like SDA and SCL for I2C and 3 GPIO pins.

The design is made in such a way that the components are plugged onto the board in a easy way. Since the MQ-gas sensors have the same pinout, they are easily replaceable and different types of sensors can be plugged-in in order to test various setups. This is according to requirement DR-11. For the TTGO ESP32 a double row of holes has been designed. The first row at each side is used for the pin headers where the ESP32 can be plugged-in. The second row is meant for additional connections to certain pins of the ESP32 later on, without the need of redesigning a whole new PCB. The leading idea behind this design has been flexibility. That is also the reason that some additional holes have been designed for GPIO connections, SDA and SCL connections and ADC connections.

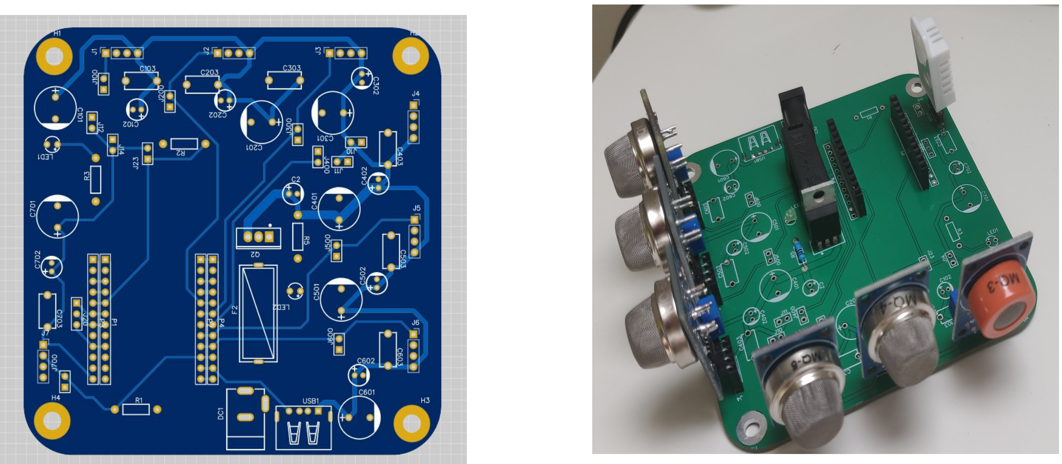
In order to make the design as simple as possible every component is powered via the USB-C connector on the ESP32 board. The input voltage is 5VDC, accomplishing requirement DR-05. The ESP32 connector has a on-board voltage regulator, converting the 5VDC input to 3.3VDC. The gas sensors are powered using 5VDC, the DHT-22 sensor is powered using 3.3VDC. Since the board contains only 3 gas sensors, this way of powering is suitable and the ESP32 is not overloaded.

After designing the PCB, the PCB has been produced and was delivered within one week. Subsequently, soldering and placing the components was done. Since the design consists of pure connections, testing and validating the design could be immediately done, by having a look at the functioning of the board. The connections from the sensors to the ESP32 were correct and every component was powered in the right way. The schematics of this design can be found in Appendix F.

5.5. Implementation 3

The main goal of making an improved version of our PCB, is to improve the data gathering. Therefore, the slots for the gas sensors have been expanded from 3 to 6 sensors[DR-01]. To see the effect of capacitors on our sensor data, in order to improve the sensor output values, capacitor slots have been added [DR-17]. Unlike the previous design, the module is now supplied voltage through a 5VDC adapter of Momo Medical, since it is easier to place and the design becomes smaller[DR-05, DR-14, FR-12]. It could happen that different adapters are plugged-in accidentally, therefore an mosfet is added to protect the module against reverse polarity[DR-06]. The module should also be able to prevent itself from being damaged severely when a short circuit occurs, therefore a fuse is added[DR-07]. Next to this an LED with a button are added to give the option of physical data validation by pressing the button if a someone defecated. Also an LED is added to show that the module is powered successfully [DR-18].
An additional future is the copper ground plane on both sides of the PCB, this reduces the electrical noise

of the data paths[DR-17].



(a) A 2D view of the second version of the PCB design.

(b) Assembly of the second PCB design (100mmx100mm) before encasing.

Figure 5.2: Figures of the second PCB design.

5.6. Implementation 4

Implementation 4 is the final PCB-design of our project. The goal of this design is to make it usable in the nursing homes. To make the design compact and easy to place in nursing homes, a octagon form of the PCB has been made[DR-09, DR-14, FR-12]. Next to this all the capacitors in the data path of the sensor have been removed. After testing, described in Section 5.8, the capacitors did not improve the signal performance. Besides it saves space[FR-12]. Also all the sensors and the ESP32 will be directly soldered on the PCB[FR-12]. Like the previous design, a double ground plane is used. However since the ESP32 is directly soldered on the PCB, the antenna could have problems sending and receiving signals, therefore an external antenna is used, which can be connected to the ESP32 via an U.FL connection[1].

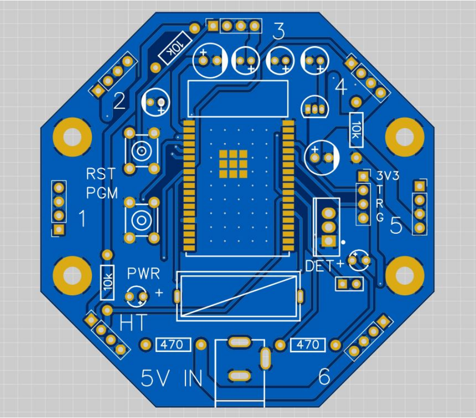


Figure 5.3: A 2D view of the final version of the PCB design

5.7. Case design

This section will discuss the design of the case. Since several requirements are directly related to this design it is important to explain the design choices made. During the whole project several case designs have been made. Only the final design will be presented in detail, parts of the other designs will be used in order to explain the techniques used for meeting the requirements.

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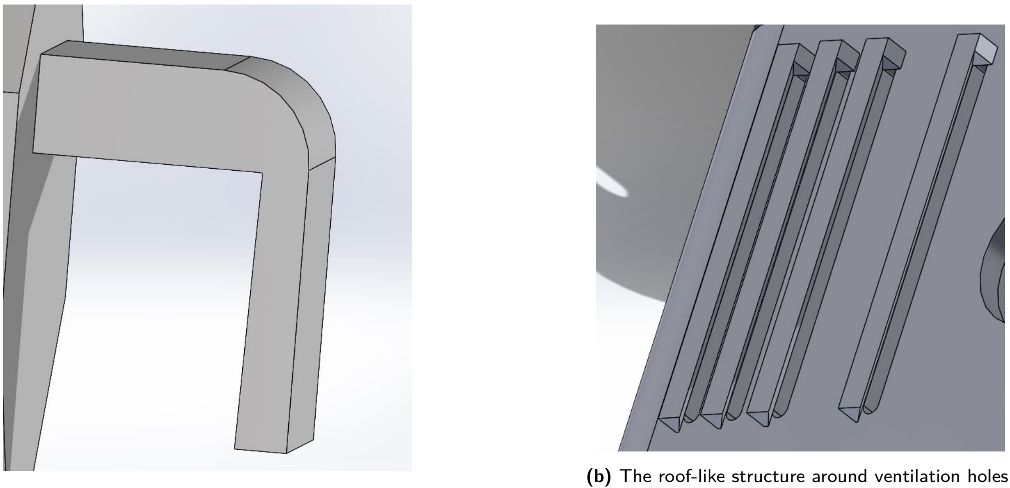
[1] Hirose U.FL is a miniature RF connector for high-frequency signals (up to 6 GHz).

Waterproof

One important requirement for the design is the ability of being waterproof [DR-08]. A case has been designed in order to protect the electronics against water. In Subsection 5.7 it will be explained that some ventilation holes are needed in order to use passive cooling for the electronics. However, such holes make the design vulnerable for water or other fluids. Therefore a roof-like structure, see Fig. 5.4b, has been designed. This will largely avoid spilled water coming into the case. Another simple way of avoiding water coming in, is making the ventilation holes on the bottom side of the design. This technique is used in the final case design.

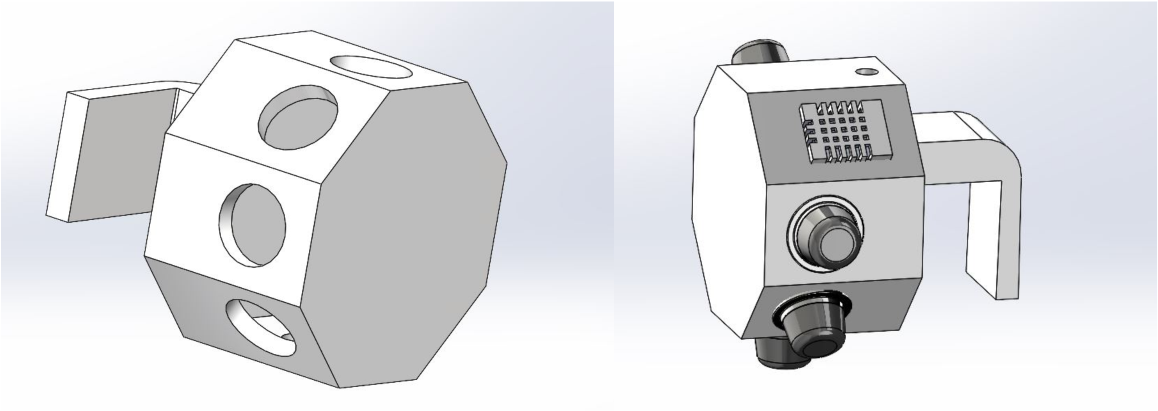


(a) The bed clip design.

(b) The roof-like structure around ventilation holes.

Figure 5.4: Features of the case design.

Since the sensors need to protrude out of the case, holes are made in the case. After doing a watertest, see Section 5.9, it became clear that the gas sensors itself are waterproof. Probably, the water is evaporated quite quickly due to the heater elements inside. In Fig. 5.5 the final design, with the holes with the gas sensors protruding out, is visible. The edges of the sensors could be glued to the edges of the case in order to make this waterproof.



(a) The holes for the gas sensors in the case.

(b) The gas sensors pointing through the case.

Figure 5.5: The final case design.

Finally, the design consists of a top and bottom part [DR-12]. If everything inside the box is placed in the correct way, this top-plate could be glued onto the bottom plate, to make it fully waterproof. Moreover, the

DC-jack on the PCB is directly glued against the side of the case, so also via this hole no water can come in.

Cooling

According to temperature testing, the gas sensor's shell gets a temperature of around 50 °C. Furthermore, after some time of operation the ESP32 processor chip and the voltage regulator gets hot as well. This means that cooling is also a topic to consider. However, to make a waterproof case, see subsection 5.7, while at same time support cooling for the interior, makes it quite complex.

The first question to answer is whether active cooling is needed. Like mentioned priorly, the components get temperatures around the 50 °C. This is warm, but not dangerously hot. Therefore, it is allowed to have the gas sensors sticking out [DR-09]. Although active cooling could help reducing the component temperatures, there are important disadvantages. First of all a fan adds more power consumption to the design. In addition the fan can give noise, which could be unwanted during the night. Finally, the influence of the moving blades on the air flow in the room is important to consider. Since the air flow is important for the gas sensors in order to catch the gasses to measure, it is not desirable to affect these air flows by a fan. Although, the fans could also be used in a positive way, letting the air flow going along the sensors, it has been decided not to use active cooling, to make it less complex. Therefore, passive cooling has been implemented, by making ventilation slots in the design. This is based on the realistic assumption that the ambient temperature is below the 50 °C and thus will cool the components.

Final case design

The final case design is an octagon like box with 6 gas sensors each placed on a different side. The DHT-22 sensor and the DC-jack are placed on the remaining two sides. The design is robust with 4mm thick walls [DR-10]. The design consists of a top-plate and a bottom-box, so it is easy to mount the PCB inside and place the sensors in the right spot [DR-12]. Replacing sensors is a matter of opening the box by removing the top-plate [DR-11]. Due to the octagon like shape it does not contain sharp edges [DR-09].

Detecting the gasses of solid stools is more reliable in the near proximity of the solid stool, see for more information appendix D. Therefore, the optimal placement of the design is as close as possible to the patient. For this purpose a bed clip has been designed (See Fig. 5.4a). In this way it is easy to hang the device in close vicinity of the patient. During installation the only things which needs to be done are hanging the device on the bed of the patient and plugging the adapter in a power socket [DR-14].

5.8. Noise analysis

As the information from the MQ-sensors is carried over an analog signal, electrical noise will necessarily create a discrepancy between the measured and actual output. Quantization noise from the ADC further decreases the signal-to-noise ratio (SNR). Some properties of the noise in this solution are discussed and mitigations are presented.

There are roughly three 'inputs' were noise could be added to the sensor signal. Firstly, the noise could be added by an unstable voltage divider voltage, caused by an unstable power adapter voltage. Also thermal noise could have impact on the sensor signal. Secondly, noise could be added while the signal is transmitted via the PCB to the ESP32 Rover. Finally, noise is added due to quantization noise from the ADC.

Since thermal noise can be modeled as white noise in this setup and the magnitude is relatively small assuming a reasonable bandwidth, this kind of noise can be ignored. The same holds for the noise added by the PCB. In order to reduce this noise, the sensor signal lines were not placed on top of noisy power lines, during the design. Finally, the quantization noise was causing problems during the analog to digital conversion, however a method of multisampling is used to reduce the noise to an acceptable level.

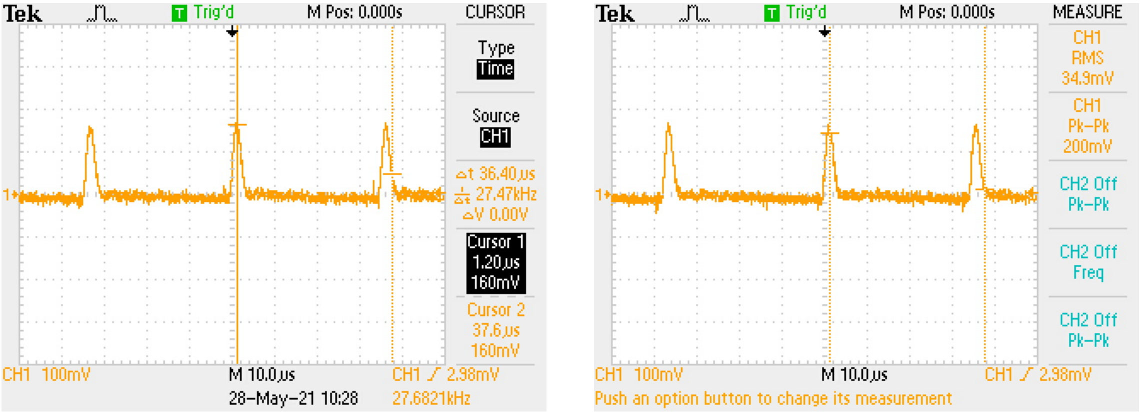
Noise of the power adapter

The power adapter noise, is not negligible. The characteristics of the adapter of Momo Medical, which is used for the device, is shown in Table 5.2. Fig. 5.6a and 5.6b show a trace of the power line ripple with 6 sensors attached.

Table 5.2: Characteristics of the adapter of Momo Medical.

Adapter 5V Momo Medical	
Ripple (Vpp) no load	160 mV - 180 mV
V_out (V)	5.12 V - 5.24 V
I_max (A)	1 A

The measured ripple from Fig. 5.6b exceeds the rated no-load ripple from Table 5.2. Fortunately, the frequency of this ripple is relatively high, as can be seen from Fig. 5.6a. The signal exists in frequencies of less than 1 Hz, so the ripple at over 20 kHz can easily be filtered out with a lowpass filter.



(a) Trace of the adapter's voltage with frequency information.

(b) Trace of the adapter's voltage with amplitude information.

Figure 5.6: The adapter voltage traces.

Noise Mitigation

As mentioned in Section 5.8, most noise is present at frequencies over ten times the signal frequency, so filtering is possible. The implementation of this filtering behaviour is described in the paper on the device's algorithm and communication [22]. According to their results, the measured noise was reduced by a factor of ten by using multisampling. Their technique was to use the average of multiple measurements taken in rapid succession as an estimate for the actual value of the sensor. Taking the average of multiple samples implements the filtering behaviour that was presented as a possibility. As this filtering is done after the information was sampled by the ADC, quantisation noise is also reduced. The overall Signal-To-Noise ratio (SNR) calculated is 18dB. This SNR-value is not causing any problems during the operation of the device.

5.9. Reliability

Making a device which will be used in the human-care context means considering reliability of the device as well. This section will discuss in detail the topics like sensor damage, sensor drift and power delivery.

Sensor damage

Since the sensors are protruding out of the case, there is a risk of damaging them. Since these sensors are the core of the system it is important to avoid these sensors being damaged or to notify the user if a sensor is damaged in order to make the system reliable.

The device will be used in nursing homes. Therefore several tests have been done to check whether the device is able to handle all kinds of events occurring in a nursing home.

One of these events is water spilling. The sensors have been tested for their ability of functioning properly when water has been spilled on them. This has been done by placing the sensor in a plastic cage, connected to a power supply outside the cage. The power supply was limited to a maximum of 1A. Hence in the case of a short circuit there is no danger of damaging the power supply or harming people doing the experiment. As it turned out the sensor was still working properly when it was fully underwater, hence water spilling is not a big deal for the safety of our design.

As the life-time of gas sensors is limited, they could give invalid outputs over time. This is detected by the algorithm [DR-16]. Based on the invalid output, the nurse gets notified that a sensor has been broken. In this way the reliability of the device is guaranteed.

Sensor drift

Another way of getting unreliable sensor outputs is the influence of sensor drift. Sensor drift occurs in two ways: short-term drift and long-term drift. Short-term drift can be caused by temperature and humidity changes or a changing gas flow. Long-term drift characteristics can occur in case a chemical gas sensor gets poisoned over time or the internal resistances of the gas sensor change over time. It is therefore useful to have a look at possible drift characteristics. Based on that information a conclusion regarding the necessity of drift compensation can be given.

Like mentioned prior, important factors causing short-term sensor drift are the temperature and humidity of the environment. Based on the plots in the datasheets of the MQ-gas sensors it can be concluded that the effect of temperature and humidity is significant [21]. For now, an additional humidity and temperature sensor is place on the PCB board. This sensor measures the temperature and the humidity of the environment. Based on these values the output values of the gas sensors are compensated. The effect of airflow fluctuations was not considered during this project, but it could potentially lead to short-term drift effects as well.

Long-term drift is an unique characteristic to each individual sensor. Even sensors of the same type, due to variations in the production, can have different long-term drift characteristics. Therefore, replacing a sensor, although its the same type, during the lifetime of the system could change the output signal of the system and making the system less reliable. Besides, the output values of sensors can either increase over time or decrease over time [29]. Since the MQ-sensors are MOS-based devices, their stability is usually 1 year or more [29]. Since the lifetime of the device should be at least 2 years [FR-10], this could become a problem. A possible correction method is explained in [29], which could be used to meet requirement [DR-17]. However, during this project it was not possible to further investigate long-term sensor drift effects, since these effects did not occur during the project period. Therefore, they were neglected.

Power delivery

An important aspect to consider while making a product for medical use, is the reliability of power delivery. The product in development will be used in order to relief the workload of nurses and to increase the comfort of patients. Since lives are not immediately at risk if the power delivery to the product would fail, it will not be a big deal if the product does stop functioning for a while. Therefore, the implementation of a backup battery has been considered, but is not implemented. It is simply not necessary.

Although it does not directly bring lives into danger if a device stops working, it would be convenient for the nurses to know if that is the case. Therefore, the main system sends a heartbeat every 5 seconds. When a single device does not react to the heartbeat it is known that there is something wrong with the device. By then the nurse will get a notification.

6

Algorithm and communication

This chapter briefly summarizes the work done by the other subgroup. They worked on the algorithm and communication. For more information please read their thesis *eNose, An electronic nose for solid stools detection* [22].

6.1. Algorithm

Different algorithms have been developed in order to detect solid stools. However, due to the cross-sensitivity of the gas sensors filtering was needed to distinguish solid stools form other gas emitting objects, like deodorant or cleaning products. Initially the algorithm worked with a threshold value and a rolling mean. In order to improve the discrimination between the emitted gasses, also the option of machine learning has been explored. Fig. 6.1 shows the second and final version of the algorithm. As can be seen, the algorithm recognized the peaks caused by solid stools. It does neglect the peak caused by heating up the sensor (the starting spike) and the peak caused by spraying deodorant.

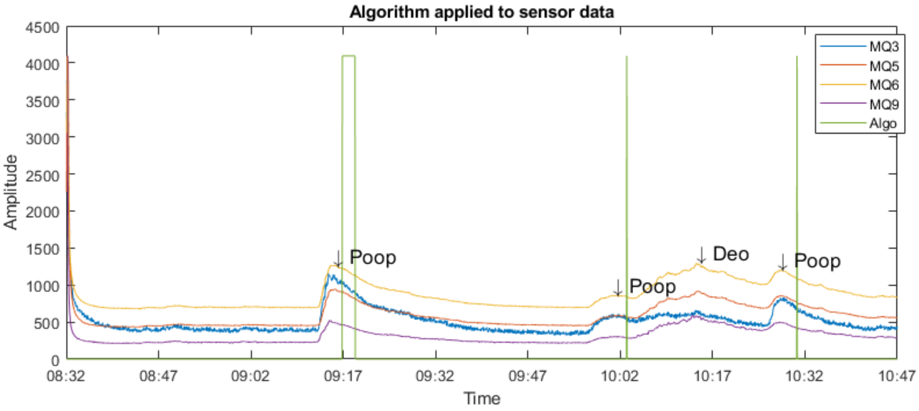


Figure 6.1: Second and final version of the algorithm applied to the dataset.

6.2. Communication

The software group added the feature of WiFi communication to the server. Therefore, FR-08 and DR-03 are met. In addition, the features of Firmware Over The Air (FOTA) and Parameters Over The Air (POTA) have been implemented. In this way WiFi settings and firmware can be changed remotely.

While connected to WiFi, the device send a Hyper Text Transfer Protocol (HTTP) request to the server. Via this request it is checked whether new firmware is available and updating needs to be done. If no new firmware is available, it will send within a certain time frame a new request. If new firmware is available, the server sends a post request and the firmware will be updated. After the device reboots, it works with the new firmware.

7

Integration and testing

This chapter discusses the final integration of the hardware and software into one device. Both, the working principle of the device and the way it has been tested are explained.

7.1. Device integration

In order to integrate the design into one product three main steps have to be done:

- Assembling the PCB
- Uploading the code onto the ESP32 WRover
- Mounting the PCB into the Case

For the final design, the code made by the software subgroup is uploaded via the Universal Asynchronous Receiver-Transmitter (UART) protocol. A Universal Serial Bus (USB) to UART converter is used to program the ESP32 WRover by means of a laptop. After uploading this code, the software updates are done via OTA (See Chapter 6).

In order to operate the device, it should be attached to the bed of the patient by means of a bedclip (Section 5.7) and the device should be powered by the power adapter [FR-09]. In addition, the sensors have a warm-up time of approximately half an hour. After this time the sensors give a stable output.

7.2. Device testing

The initial idea to test the system as a whole, was to simulate the existence of solid stool using a test bench. The idea, based on the mixed flow gas testing chambers, was to make a gas chamber with controlled flow of incoming desired gasses. This mixture of gasses would create an optimal testing environment inside the chamber. However, after discussing the idea with dr. ir. Ger de Graaf it turned-out to be far beyond the scope of this project. Firstly, due to limited expertise on the chemistry domain. Secondly, certain specific and expensive equipment needed for building such a test bench was out of reach during this project. Therefore, a new testing strategy was developed. The new testing strategy was divided into three phases:

- Testing the gas sensing ability
- Testing and developing the algorithm
- Testing in the nursing home

Testing the gas sensing ability of the sensors has been described in Section 4.2.
However, for the algorithm development, representative data is needed. Since it is difficult to place devices in nursing homes for data gathering, it was decided to first place the devices in restrooms and use this gathered data. For this purpose PCB designs have been made, like described in Section 5.4 and 5.5. The modules were distributed and placed among the team members restrooms.

To facilitate the process of data gathering, some additional features were added by the software subgroup. In case the device is turned-on, it connects automatically to the server via the WiFi protocol. A visualization program, called Grafana, has been connected to a database, which has been connected to the server. Therefore, the sensor values of each device are visible in Grafana in real-time. By these means, the data was easily accessible during development of the algorithm. In order to label the data, the users either filled out an questionnaire via a QR-code or pressed a button on the device, while defecating, see Fig. 7.1.

Based on the selectivity[1] of three devices, the overall performance has been calculated to be 73% [22]. A total of only three devices were used for the calculations. Collecting more data with more devices could improve the selectivity of the device [22].

The final testing step will be testing the devices in nursing homes. To be allowed to place the device in nursing homes, both permission and safety have to be granted. An experimental setup has been written (See appendix E for the document). This permission process is slow and therefore it was not possible to place the devices in a nursing home before the submission of this report. However, after this report has been handed in, the devices will be placed in a nursing home. During the presentation these results will be presented.

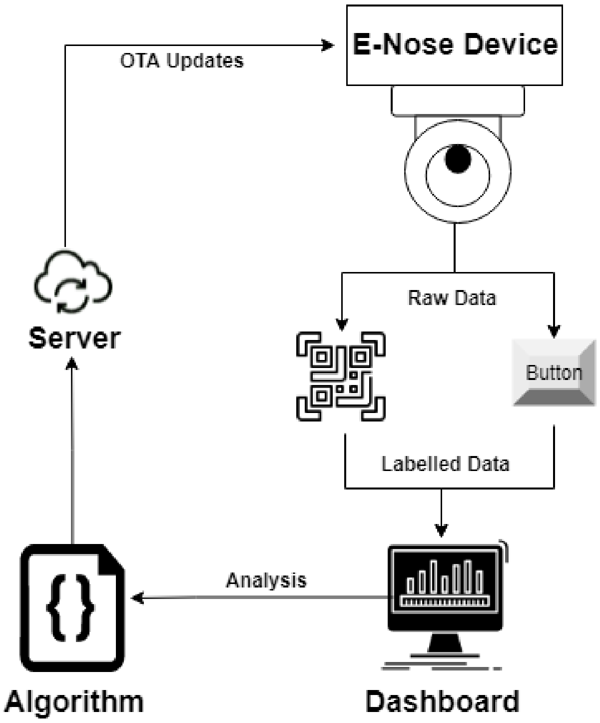


Figure 7.1: The testing setup during testing and developing the algorithm.

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[1] The selectivity means in this context, the ability of the device to correctly classify solid stools.

8

Conclusion

The aim of the project was to develop a non-intrusive device that could detect solid stools. The best possibility for detecting solid stools turned out to be using gas sensors. Based on the requirements, cheap and simple MQ gas sensors were selected, instead of expensive and high selective gas sensors. By means of sensor testing, their ability of detecting the targeted gas, CH4, was verified. Finally, MQ-3, MQ-9 and MQ-135 were selected to be the most useful sensors. Although MQ-135 is not used for the algorithm [22].
A closer look into the variations caused by humidity and temperature was taken. Both a linear and a bilinear model were used in order to predict these variations. The bilinear model is sufficient to accurately predict the variations caused by humidity and temperature.
After calibrating DHT22 sensors for humidity, it became clear that the RMSE between the linear regression model and the measurements was minimal. Thus, further calibration of the other DHT22 sensors is not needed.
Although gas sensor calibration was not possible within the scope of this project a simplified way of gas sensor calibration has been presented.

By means of several iterations a final PCB design has been developed, while the other designs have been used for data gathering for the algorithm. Also a case design has been designed, which protects the hardware against several external factors. As the overall performance of the module is 73% at this moment, making a device capable of detecting solid stool has succeeded [FR-01].

Future work

Although the main goal of this project has been met, there is certainly place for improvements, since the device should ultimately get a rate of performance of 100%. First of all, it is recommended to have a look into the more expensive and selective CH4 gas sensors. Since during this project, it has been decided to only use cheap MQ-sensors. Although the currently used sensors give promising results, a more expensive sensor could be more sensitive, ease the way of making an algorithm since the cross-sensitivity will be less and improve the overall performance.

Secondly, the design could be made more compact. Sensors on breakout boards have been used. This made the design more flexible and the development process easier and faster. However the design is less compact. In order to increase the compactness, the sensor 'hats' could be placed directly on the main PCB and the circuitry could be directly embedded on the PCB as well. This approach will make the design more compact.

Thirdly, the gas sensors could be calibrated and coupled to the parts per million value of CH4 in the air. Due to limits of expertise and cost it was not realistic to perform gas calibrations within the scope of the project. However, it is recommended to try the proposed, easier method of calibrating the gas sensors.

Finally, having a look into the possibility of using a fan for cooling and for conducting the air flow along the gas sensors could be explored. Although no research has been done for such an implementation, it could be a promising option.

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A

Sensor theory

This appendix gives a detailed explanation of the working principles of six different gas sensor types. It is based on the literature review done for this project.

Semiconductor sensors

A semiconductor sensor is a device on which a semiconductor material is incorporated. It consists of a gas sensitive resistive film, a heater element and an insulation medium as shown in Fig. A.1.
When the device is surrounded by the target gas, the gas molecules react with the surface, which produces charged ions that change the resistance of the film. This change in resistance is measured through two biased electrodes that are embedded in the device.
The heater element controls the temperature of the film to obtain optimal reaction temperature, as this can increase the sensitivity and selectivity for the target gasses (more on this later). The initial reaction of the surface with the gas is called the reception and the transformation of this change in resistance is called transduction [1].
There are several semiconductor sensors' types, that differ by their working principle, sensing mechanism and their semiconductor material. Within semiconductor gas sensors are there two main groups, oxide and non-oxide semiconductors. [2]

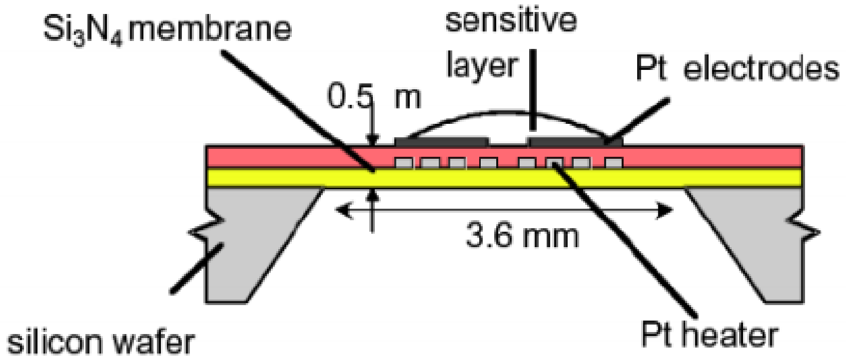

Figure A.1: Metal oxide semiconductor sensor design, Reprinted from *'Electrochemical vs. Semiconductor Gas Detection – a Critical Choice' (2009)* [1].

Metal Oxide semiconductor

One of the most common used semiconductor gas sensors are metal oxide semiconductors (MOS), which are also referred to as resistor sensors, the semicoductor gas sensors are constructed using porous sensing bodies made of semiconducting oxides, such as SnO_2, WO_3, ZnO, and In_2O_3 [3].
Semiconducting oxide sensors are in demand due to their low cost, simple operation principle, durability, ease of fabrication and a relative smaller size compared to other gas detectors, This all combined with a high gas response, as they are able to sense gasses with low concentration[4].

These Oxide semiconductor sensors have a relatively simple sensing mechanism, once these sensors are surrounded by the target gas, their resistance changes as a function of partial pressure of the gas. The target gas interaction with the surface stimulates an electronic change in this oxide surface, this surface electronic change translates into an electrical resistance. The type of the oxide material and the gaseous ambient determine the reaction of the resistance, for example, using an n-type oxide the resistance of the sensor increases when oxiditive (NO_2, O_3) gasses are present and decreases on exposure to inflammable gasses (H_2 CO CH_4). [2]

The performance of these sensors is determined by three independent factors, the receptor function, transducer function and utility (see Fig. 3.2). The receptor function refers to the oxide surface interaction with the ambient gas. , transducer function is the ability of transforming this induced surface properties into electric signals. The last factor is the utility which is the accessibility of inner oxide grains to the target gas . Modern oxide semiconductor gas sensors are usually doped with a appropriately chosen foreign material to improve the gas response, which is also referred to as sensitivity, this material loading can influence the three mentioned factors and thus improve the performance [5].

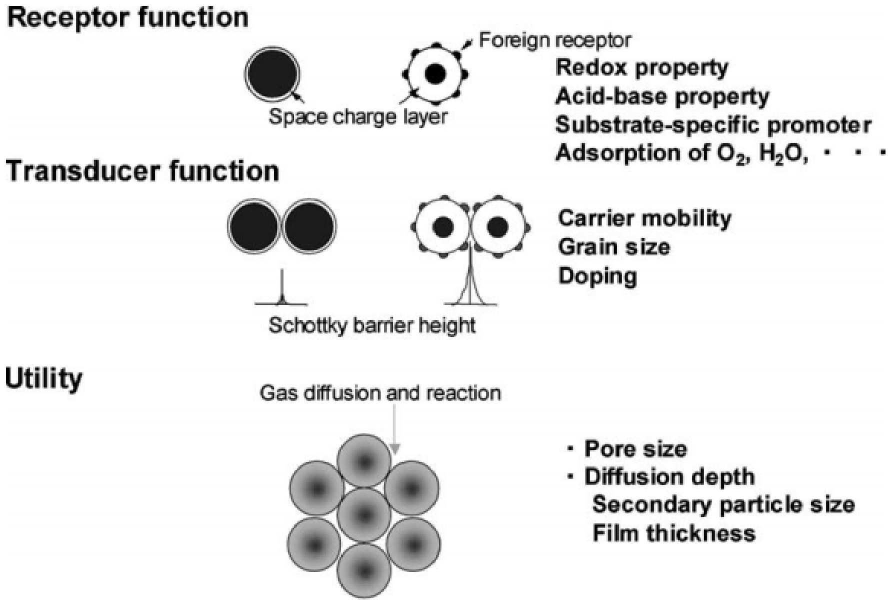

Figure A.2: The factors and corresponding material properties that determine the performance of the device, Reprinted from *'Toward innovations of gas sensor technology' (2005)* [5].

Thin-film semiconductor

As discussed above, the utility of the oxide semiconductor can affect the sensitivity of the gas sensor. To understand the relationship between utility and the sensitivity, we observe the interaction between the target gas and the oxide surface. Once the gas reaches the semiconductor it reacts with the oxide surface, while diffusing into the bulk of the sensor.If the ratio between the reaction and the diffusion is too large the gas molecules will not be able to access the inner grains of the device, which will decrease the utility of the device thus decreasing its sensitivity [5].

Thin film semiconductors were introduced, to improve the gas response based on this mentioned characteristic, as research suggests that the thickness of the of the surface is directly related to the amount of target gas reaching the bottom of the film.

Based on this founding we conclude that the utility of the oxide semiconductors can be improved by decreasing the thickness of the firm. Thin film semiconductors have a thickness within the nanometer range

Thick-film semiconductor

Thick-film semiconductors work according to the same principle of thin-film semiconductors, as they were also introduced to increase the utility of the device. They however achieve this using highly sintered particles, which are also referred to as thick film.
Research suggest that this construction enhances the utility thus improving the sensitivity of the device.[6] This happens as the electrons pass from one grain to the other crossing the grain-grain Schottky barrier, which optimizes the impact of the surface charge onto the concentration of free charge carriers. [7]
Thick-film semiconductors are not only used as gas detectors, they are also used as pollutant gas reducers through catalytic conversion.

Applications of oxide semiconductor gas sensors

Metal oxide semiconductors (MOS) are largely used in several industries due to their multiple benefits that were discussed priroly. In this section we will illustrate how these gas detectors are utilised for detecting volatile organic compounds (VOC's) concentrations.
Monitoring VOC's is becoming relatively important now days, it is used for indoor air quality, environmental issues, fire detection and other industrial and health applications.
Compared to other monitoring techniques, gas semiconductor VOC monitoring is regarded as high-performance solution for a relatively low price. As it can achieve ppb (or even sub ppb) level sensitivity for application-specific systems and for prices as low as 10 euros.
MOS sensors that are used for general VOC monitoring applications are commercially available for an even lower price range and can provide ppm level detection [8]. The drawback of MOS's, when detecting VOC's is the poor selectivity. This however is being tackled using several methods, one of them is temperature cycle operation (TCO), which is based on the chemical principle that different gasses show different optimal interaction with the surface based on the surface temperature, for instance gases as CO or H_2 will react at relatively low temperature while other gases as CH_4 will have optimal reaction with the surface at higher temperature. Using this technique preferred VOC's can be detected down to concentration of 1 ppb in the background of other VOC's of several ppm, and against changing humidity.[9].
Improving the selectivity of MOS sensors for target gasses have also been investigated through other approaches. Practical examples of these are:

- The use of a WO_3 thick film semiconductor detector, while applying a catalyst to a limited area of the film, to selectively promote the sensitivity of aromatic hydrocarbon gasses, as these gasses are poorly detected by commercially available sensors.
Using WO_3 thick film in combination with the novel catalysing method, allowed the detection of traces of VOC gasses at ppb levels [10].

-The use of CuO semiconductor sensor to improve the sensitivity and selectivity for H_2S , as other MOS sensors show a poor performance for the gas. CuO is a p-type semiconductor which has a high adsorption capacity to H_2S compared to other gasses. The CuO p-type MSO has proven to have an outstanding selectivity and a high sensitivity for H_2S, and is able to detect very low concentrations, down to 0.1 ppb [11].

These two practical examples serve as an inspiration and will help us understand how researches are tackling the low selectivity issues of MOS sensors. This knowledge is highly valuable, and will be considered when choosing the detection sensor and method for our project.

Thermal conductivity sensors

Thermal conductivity sensors are meant for detecting gasses with thermal conductivities greater or smaller than air, like hydrogen and methane. The working principle is based on the measured heat loss form a hotter body to the cold element by means of thermal conductivity via the gas [12]. This conductivity is determined by the target gas with respect to the reference gas. The most simple reference gas is air.

The conductivity of heat will go from the heater resistor to both temperature sensors via the target gas and relative gas (See Fig. A.3). In case the target gas deviate from the relative gas, the conductivity will be changed and could be correlated with the output signal as follows: because the heater resistor has a fixed temperature, the temperature measured by the temperature sensors is correlated with the conductivity

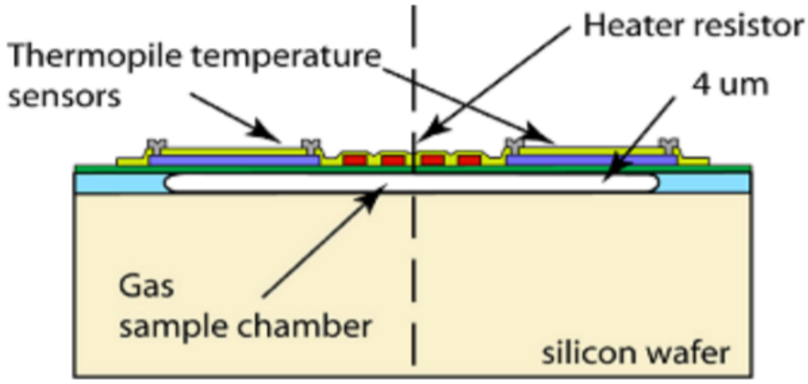

Figure A.3: A thermal conductivity gas sensor layout [12].

of the target gas. The temperature sensors will in turn translate this temperature into a resistance. This resistance is thus correlated with the conductivity of the target gas. Therefore the output signal could be used for determining the target gas.

There are some commercially available gas sensor types based on the thermal conductivity principle. An example is the VQ31M gas sensor. This sensor, with a price tag of €150, is suited for detecting methane at room temperature and ethane at higher temperatures (around 100-200○C). However, the output voltage is non-linear with the concentration of the gas [13].

The sensor is robust and simple, however it is difficult to make this sensor selective in an environment with all kind of gasses. Besides, due to heating of the bridge, the power consumption of this specific sensor is at least 350mW. The sensitivity of this sensor for methane is defined as $2.5mV/\%volume$.

Catalytic sensors

This type of sensor is mainly used for detecting flammable gasses. Think of ethane, methane but also other organic gasses like acetone and hydrogen. The main principle of a catalytic sensor is making use of catalytic combustion[1]. In general two different kind of catalytic sensors could be indictated: the pellistor catalytic sensors and the thermoelectric gas sensors [12]. The temperature change of propane is around $\Delta T = 7.5K$ per 100 ppm. For methane this is around six times smaller. Which means a valid signal for flammable gasses is achievable [6].

The pellistor catalytic sensor

The pellistor type gas sensor consists of two beads and two resistors (See Fig. A.4). One active bead with a catalyst[2] and one inactive bead. Together with the resistors, this does form a Wheatstone bridge. Both beads could be heated up by an external power supply. The heating temperature is within the range of $300\circ$C - $500\circ$C [12]. This temperature depends on the gas to measure. Due to the high temperature and the catalyst on the active bead, the target gas will ignite, which in turn does increase the temperature of the active bead. This change of temperature will change the resistance of the coil, which causes an imbalance in the Wheatstone bridge. This imbalance can be used as an output signal indicating the concentration of the target gas.

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[1] Catalytic combustion is a chemical process which uses a catalyst to speed up the desired oxidation reactions of flammable gasses in order to reduce the formation of undesired products

[2] A catalyst is a substance used to increase the rate of a reaction, without being consumed in the process. However in reality, the catalyst will become poisoned and become deactivated within a certain timeframe.

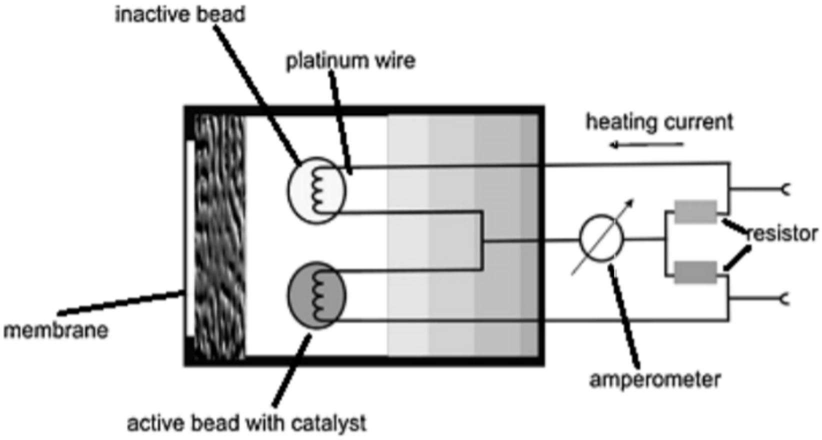

Figure A.4: A pellistor catalytic sensor layout [12].

Although this principle is simple, there are some disadvantages or difficulties implementing this type of sensor. First of all, selecting the right catalyst, the right bead material and the right heating temperature for a specific target gas is difficult [6]. Most of the time there are multiple gasses igniting as well and thus interfere with the target material. This could lead to false positives. Secondly, the catalyst could become deactivated due to other molecules form the air or from the ignition reaction sticking at the active parts of the catalyst. The time it takes to deactivate the catalyst does determine the lifetime and sensitivity of the sensor [6].

Increasing sensitivity by means of filters

The problems described before, causing interference or even worse, causing deactivation of the catalyst could be (partly) avoided by using filters. Examples of filters could be activated charcoals or gas-permeable membranes [6]. A disadvantage of these filters is that they do not permanently remove the interfering gasses, but rather trap these gasses for a certain period of time and release them at a lower concentration. Another important factor to determine whether a filter is suited, is the so-called lifetime of the filter. Finally it is important to make sure that the gas to be detected is not blocked by the filter as well.

The thermoelectric catalytic sensor

The second type of catalytic sensors is the thermoelectric sensors. These sensors uses both the oxidation process and the Seebeck effect [3]. The detector heated up at the right temperature and having the right catalyst causes a catalyzed exothermic oxidation reaction. The quality of the output signal is largely dependent on the detector material with its related Seebeck-constant. Besides, the same disadvantages mentioned in section A can be directly applied to these kind of sensors. In recent years also VOC sensors of this type have been developed.

Commercial available

There are some combustible gas detection sensors mainly used as safety sensors in areas with flammable gasses. An example of this type of sensor is the TGS-813 sensor [14]. This relatively cheap sensor with a price tag of €20-€30 euros, is mainly meant for detecting gasses like methane, propane and butane. However, it is not really selective for one of these flammable gasses, but the characteristics of these gasses are quite similar and therefore the sensor will have cross-sensitivity for all these gasses. The sensor detects these gasses starting from a concentration of at least 500ppm.

---

[3] The Seebeck effect is the direct relation between temperature difference and voltage difference. As a result of a temperature difference between two points on a conductor or semiconductor material, a voltage difference across these two points will occur.

Conclusion

In general, the catalytic sensors are simple types of sensors for detecting mainly flammable gasses. However nowadays, this technique is also more used for detection of organic gasses. The technology is simple and therefore the production costs are low. On the other hand, the power consumption could be high according to other type of sensors, due to the needed heating power. In addition, it is difficult to achieve a very selective gas sensor.

Optical sensors

Optical gas sensors operate by measuring the absorption and scattering at defined optical wavelength. Certain gasses will have peaks at specific wavelengths. This setup requires a light emitting element, photo detecting element and a filter to prevent filters fluorescence/phosphorescence effects [12]. A special subclass of optical sensor is the NDIR (Non-dispersive infrared) sensors which uses infrared as emitted light. It is however difficult to differentiate between different hydrocarbon (e.g. methane, ethane, propane, butane etc) as the absorption characteristics are similar to each other [15].

The optical sensor's electrical components can be separated from the gas chamber through which the light beam travels, this is ideal for sensing combustible gasses. Hence, in academic literature is written extensively about optical sensors for measuring methane and ethane. Zheng et al. developed a dual-gas sensor that can detect ethane in very small concentrations from .36 parts per billion, and methane from 1.7 ppb [16]. Massie et al. used near-IR leds to develop a low-cost portable methane detector that can detect from 100 ppm [17].

Commercial available sensors are widely available but carry a significant price tag that start from around 150 euros. An example of commercially available sensor is the IR12BD from SGX sensor tech that can detect from 50 ppm methane and other hydrocarbon [18].

Acoustic Wave sensors

Acoustic wave sensors work based on the principle that a very high frequency acoustic wave traveling through or on a surface will change characteristics, e.g. amplitude or phase, of the wave itself. The sensors will generate acoustic waves which will be distorted by the gas present in the gas chamber and the distorted signal will be captured to create a electric signal again. This distortion consists out of amplitude or phase change and is gas specific. Similar to all categories of gas sensors, their are various subcategories: Thickness-Shear mode resonator, Surface Acoustic Wave, Acoustic plate, Flexural Plate, Bulk-wave, Surface Transverse wave, Love wave, and Thin-Rod Flextural-Wave [19]. To keep the literature review concise, the difference between the subcategories are omitted. In general are the sensors not compact and portable [20]

A surface acoustic wave sensors developed by Wang et al. in 2015 could detect a methane mixture from up to .2% which corresponds to 2000 ppm [21]. A love wave sensor developed by Wang et al. could detect methane from up to 50 ppm [22]. However, acoustic wave sensors are not widely available currently. The sensors that are commercially available are incorporated into whole analyser devices starting from 5000 euros.

Electrochemical sensors

The electrochemical sensors are based on the working principle of a chemical reaction of the target gas, resulting in an electrical signal proportional to the gas concentration [12]. The components of a typical electrochemical gas sensor are a sensing electrode, a counter electrode, a reference electrode, electrolyte, a capillary-type opening and a hydrophobic membrane [12] (See Fig. A.5).

First, the gas goes through the capillary-type opening and than diffuses through a hydrophobic membrane. Finally, it reaches the electrode surface. The reaction with the target gas results in a current flow between the counter electrode and the sensing electrode via the electrolyte. The reference electrode is meant for creating a stable and constant potential at the sensing electrode [12].

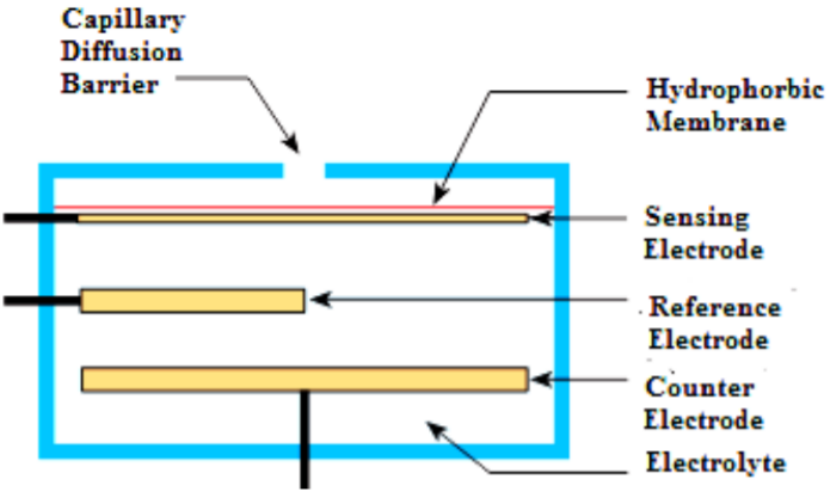

Figure A.5: A electrochemical gas sensor layout [12].

There are several electrochemical sensors commercially available. They are mostly designed for detecting toxic gasses. An interesting electrochemical sensor, might be the EC4-100-H2S sensor meant for detecting H2S [23]. It has a sensitivity of 600-1000nA/ppm, besides the resolution is 0.1 ppm, finally the starting detection level of the sensor is around 0.6ppm. The sensor has a price tag of around the €130 euros.

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B

Temperature and Humidity Correlation

Figures 4.3a and B.2 show the results of fitting two models to estimate the signal created from temperature and humidity fluctuations. For brevity in the main document, the results were shown for only one sensor. In this appendix plots for all sensors are shown, with respect to both temperature and humidity.

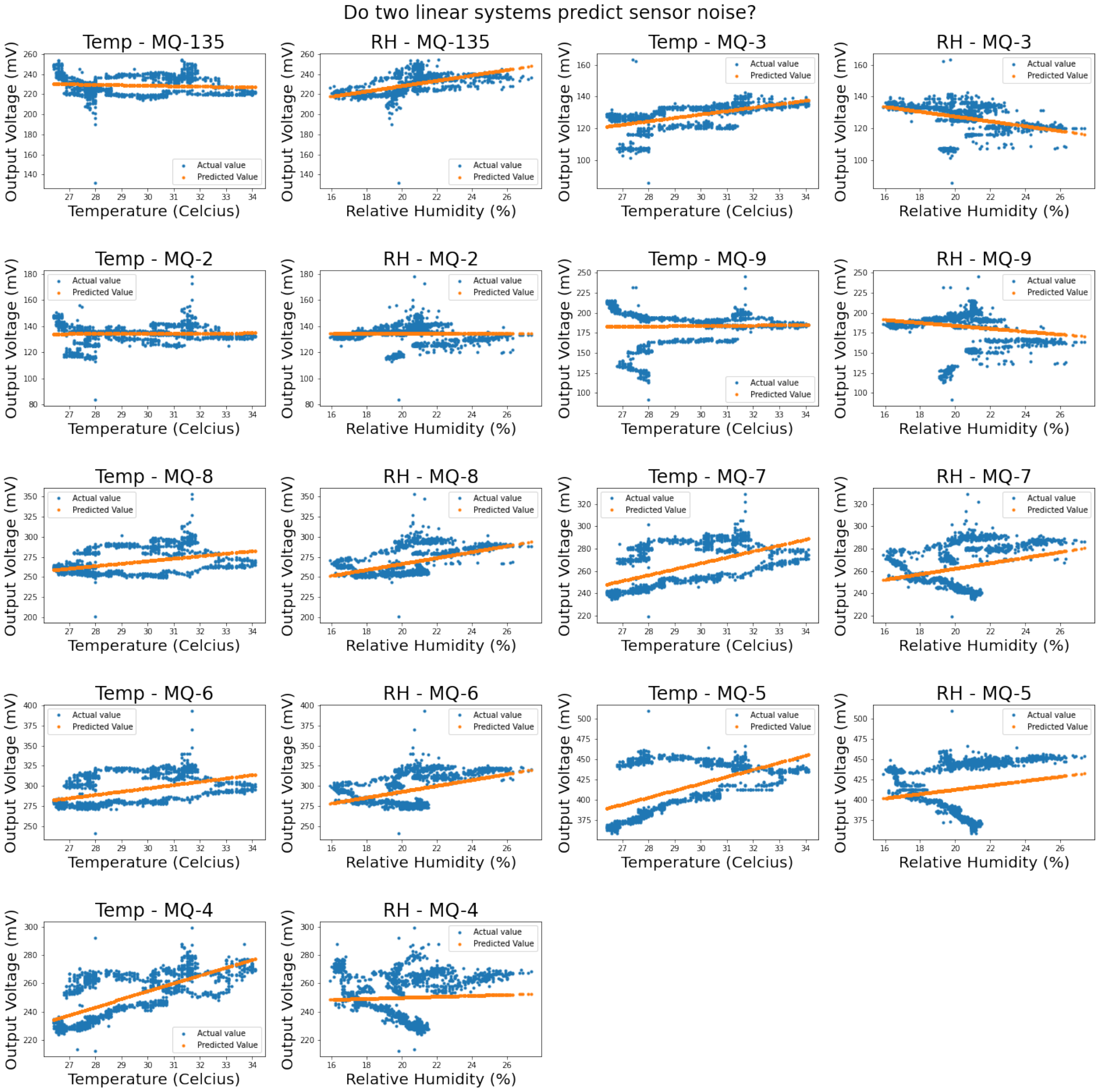


Figure B.1: Linear fits from every sensor with respect to temperature and humidity.

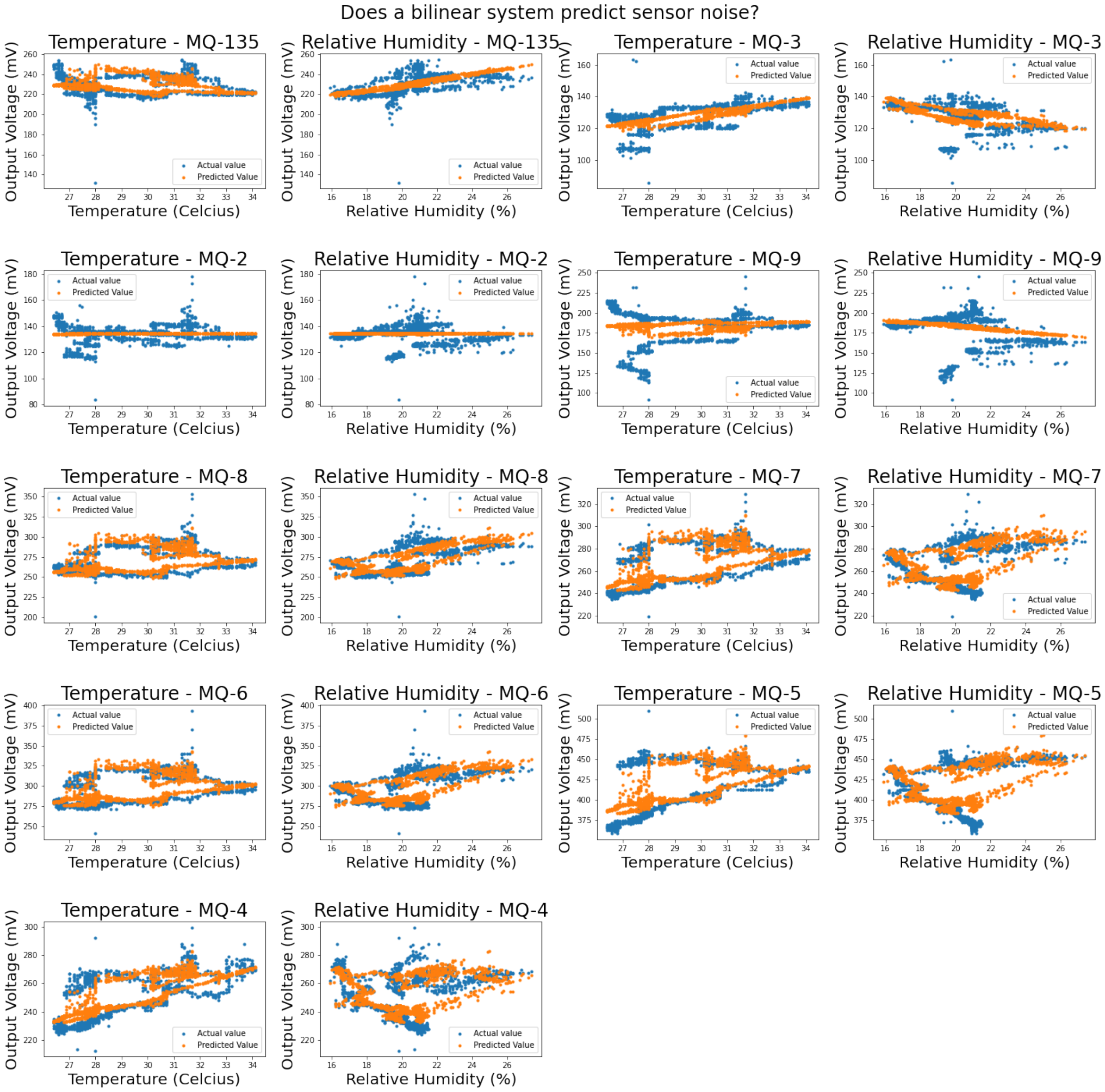


Figure B.2: Bilinear fits from every sensor with respect to temperature and humidity. Each fit is show from two perspectives, the temperature (or XZ) plane and the humidity (or YZ) plane.

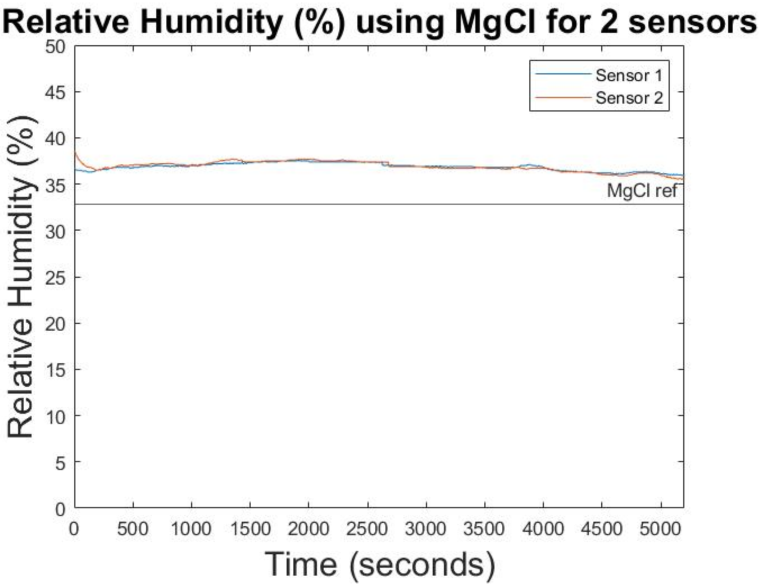
C

DHT22 humidity sensor calibration

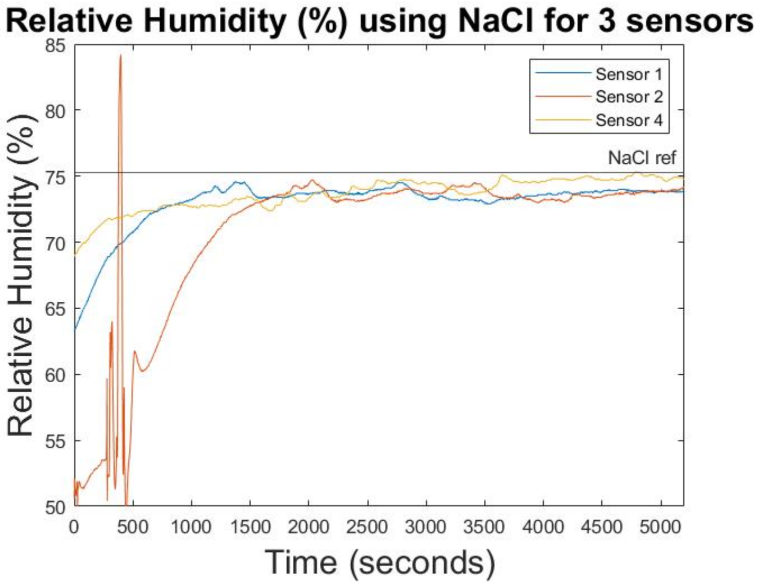
As part of the results are discussed in section 4.3, this appendix will show and explain the other results obtained during the humidity sensor calibration.
Fig. C.1 shows the relative humidity output of the sensors within saturated salt solution environments over time. All the experiments took around 90 minutes. Since not each sensor could be placed into each saturated salt solution environment, the sensors placed inside differ per salt solution.

In general it can be seen that the error between the expected level, the solid straight line called 'ref', and the sensor outputs is the largest for the LiCl solution. As mentioned in section 4.3, the values were still dropping after 90 minutes, which could indicate that for this particular salt solution the time needed to approach the reference should be much longer than 90 minutes.
In addition the error is the smallest for the NaCl solution, although the overall stability of the sensor output values is smaller.
The sensor output values in the MgCl solution environment are more stable, but their error after 90 minutes is larger, than the error at NaCl.

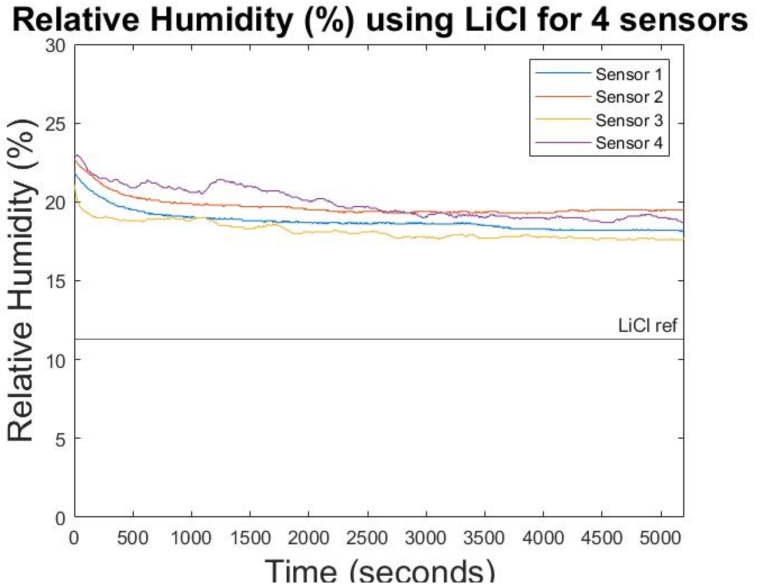
After performing the measurements a linear regression model has been made in order to calibrate the sensor. Since the error for LiCl is relatively large, both with this measurement value and without this measurement value linear regression has been applied. Using the integrated Basic fitting tool in Matlab, the plots in Fig. C.2 and C.3 were made. It can be seen that leaving out the measurement value of LiCl does increase the RMSE by 50% or more. However, the smaller the number of measure points the less valid the outcomes are. Even with the measurement LiCl, the linear model does fit the points well. Both the R^2 values are high and the RMSE values are low, meaning the model does fit the measured values well.



(a) Relative humidity of a MgCL solution for different DHT sensors.

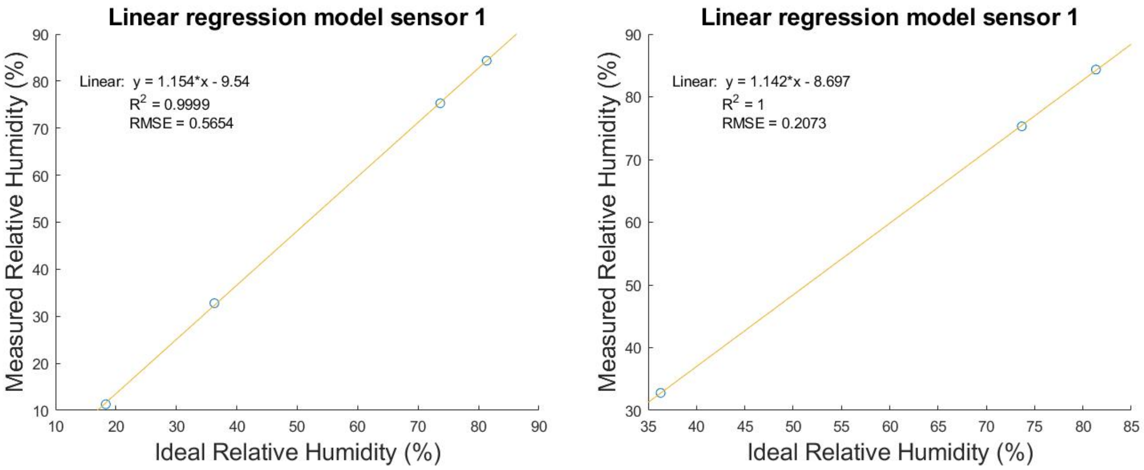


(b) Relative humidity of a NaCL solution for different DHT sensors.



(c) Relative humidity of a LiCl solution for different DHT sensors.

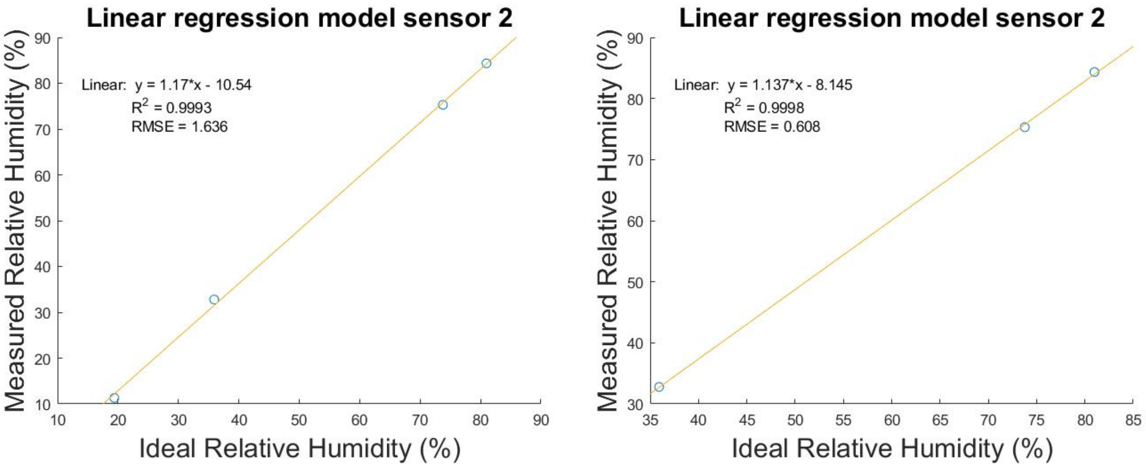
Figure C.1: The measured relative humidity's of different salt solutions for different sensors.



(a) A linear regression fit with the LiCl solution data.

(b) A linear regression fit without the LiCl solution data.

Figure C.2: Linear regression fits of the measured relative humidity against the ideal relative humidity for sensor 1.



(a) A linear regression fit with the LiCl solution data.

(b) A linear regression fit without the LiCl solution data.

Figure C.3: Linear regression fits of the measured relative humidity against the ideal relative humidity for sensor 2.

D

Sensor placement

This appendix provides a literature review of the best placement of the device. Since not all the parameters could be taken into account, mainly the gas flow and particle density will be taken into account.

Device placement and gas behaviour

With the composition known, it is also important to know how the released gasses behave in a room. The simplified movement of gas in a room can be described using Fick's first equation for massaflux [1].

$$J = -D\frac{\partial C}{\partial x} \tag{D.1}$$

With D being the diffusion coefficient, C the concentration and x the distance. The diffusion coefficient D changes for different gasses. The coefficient of the main components of the smell of stool at 25°C can be found in Table D.1 [2]. Because skatole[3] and indole[4] are solid at room temperature, they are not included in this list. A higher coefficient means the gas distributes itself relatively faster, but this also means it will disappear quicker. The latter is rather important, because it gives us an indication of what gasses are more likely to disappear faster. The chemicals with higher coefficients can be used as indicators on when to start measuring, because they spread quicker. The concentration change over time can be explained with Fick's second formula [1].

Gas	Coefficient
Methane	0.240
Carbon Dioxide	0.113
Hydrogen	N.A.
Nitrogen	0.212
Hydrogen Sulfide	N.A.

Table D.1: Distribution coefficients for main components human feces

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2} \tag{D.2}$$

Both of the Fick equations can help with describing the behaviour of the gasses, but will not be used to perfectly model the entire picture. Other than diffusion there are a lot of other factors playing a role such as ventilation and thermal imbalance causing convection flows.

However, Equation D.2 clearly shows that a device further away experiences a slower increase in gas concentration when exposed to feces. This means that devices placed closer to the source will be able to pick up the gasses earlier. Eventually, if the room is closed and the feces create enough gas, the gas will be distributed over the room equally. The bigger the room, the longer this process takes. A smaller room needs less gas to reach the same concentration as in a bigger room.

Other than that, a spot in the room for the sensor needs to be decided upon. Depending on the particle size, there could be a higher concentration near the floor or the ceiling [5]. This effect is also complemented by gravity, particles with a greater density than air, will usually be closer to the ground. The densities of the main components are listed in Table D.2[6] [7]. Skatole and indole are solid at room temperature, so that explains their larger density. The skatole and indole that are released from the feces can still be smelled

Chemical	Density [kg/m^3]
Air	1.1839
Methane	0.6567
Carbon Dioxide	1.8075
Hydrogen	0.0823
Nitrogen	1.145
Hydrogen Sulfide	1.4034
Skatole	1101
Indole	1174

Table D.2: Distribution coefficients for main components human feces

in the air for some time, because of their relative small particle size. Because of their larger density it is expected that they are more likely to fall to the ground.

The main gas released from feces is methane [8], since this gas has a density $0,657kg/m^3$ and is thus lighter than air. This coupled with the fact that gasses released from defecate are close to body temperature suggests that the gasses first move up before diffusing throughout the room. Using this it would be expected that the best place to detect gasses would be between the ceiling and the source. However, since the patients are in bed when detection is needed, the blanket should be considered. Because of the blanket, a direct path from the diaper to the ceiling is blocked resulting in the gas escaping from the sides. Concluding, placing the device at the side of the bed of the patient could be a good position.

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E

Experimental setup

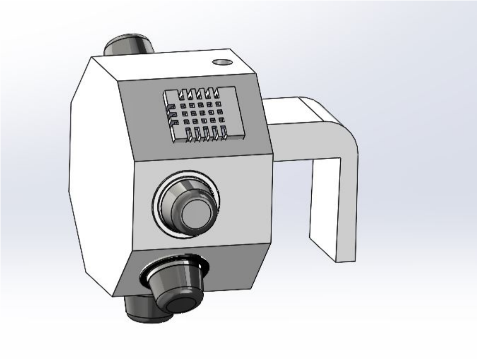
N.B.: This document has been translated from the original Dutch to English.

Introduction

As a part of the finalisation of the bachelor program Electrical Engineering, we are working on a graduation project. The project, in collaboration with Momo Medical, involves developing a product that detects defecation in nursing homes, named e-nose. Our technology improves the quality of live for patients, increases the efficiency of care and improves the daily work of nursing staff. For our graduation project, it is important to test our prototype in an environment that resembles the one where the product will eventually be used. In our case this means care homes. We hope to provide some more information in this document about our product, the method we would like to apply in your nursing home to test our product, and the justification for the data we process.

Product/technology

The e-nose is a small box that is hung on the bed, or near the patient. With its gas detection ability, the e-nose can detect human waste. It consist of a few gas sensors, which detect the gasses that are released during defecation. The information gathered by those sensors is sent to an algorithm, which can use that information to determine if there is fecal matter or not at any time. If fecal matter is present, a message is sent to the nurse, who can immediately take action.



Method

To test our product most effectively, we would like to place some of our sensors near the bed of patients suffering from incontinence. Every patient will get one device attached to their bed. As described above, a message will be sent if the device believes that the patient has done their business. It is important to then validate this belief by going to the patient and checking if they have pooped. When you are certain that the patient has done their business, please send 'yes' as a response to the text message you received. In the case you did receive a text message, but the patient has not defecated, please reply with 'no'.

Placement

Attaching the sensor to the bed is very simple. On the back of every product is a clip which can be hung from a leg of the patient's bed. The device must hang facing the outside of the bed, to ensure minimal coverage. The included adapter must be plugged into a power socket. When the adapter is properly plugged in, a green light will turn on which indicates the device is on. From that moment, the device will function and no further configuration is needed.

Privacy

As the device uses data from the patient, privacy is a major concern. By only linking the data to a room number, and not the name of the patient, the data is made anonymous. There is no link between the patient and the sensor data.

Safety

The device is contained in a solid shell which is water-tight and which protects the electronics properly. The gas sensors, which are visible on the outside, heat up to a harmless temperature. Getting hurt from the device is therefore impossible. The shell has no sharp edges and is completely safe to use. The adapter complies with EU safety regulations and the electronics inside contain safety mechanisms to prevent, for example, a short circuit.

F

PCB circuitry drawings

This appendix contains the circuitry drawings of the three PCB designs made during this project.

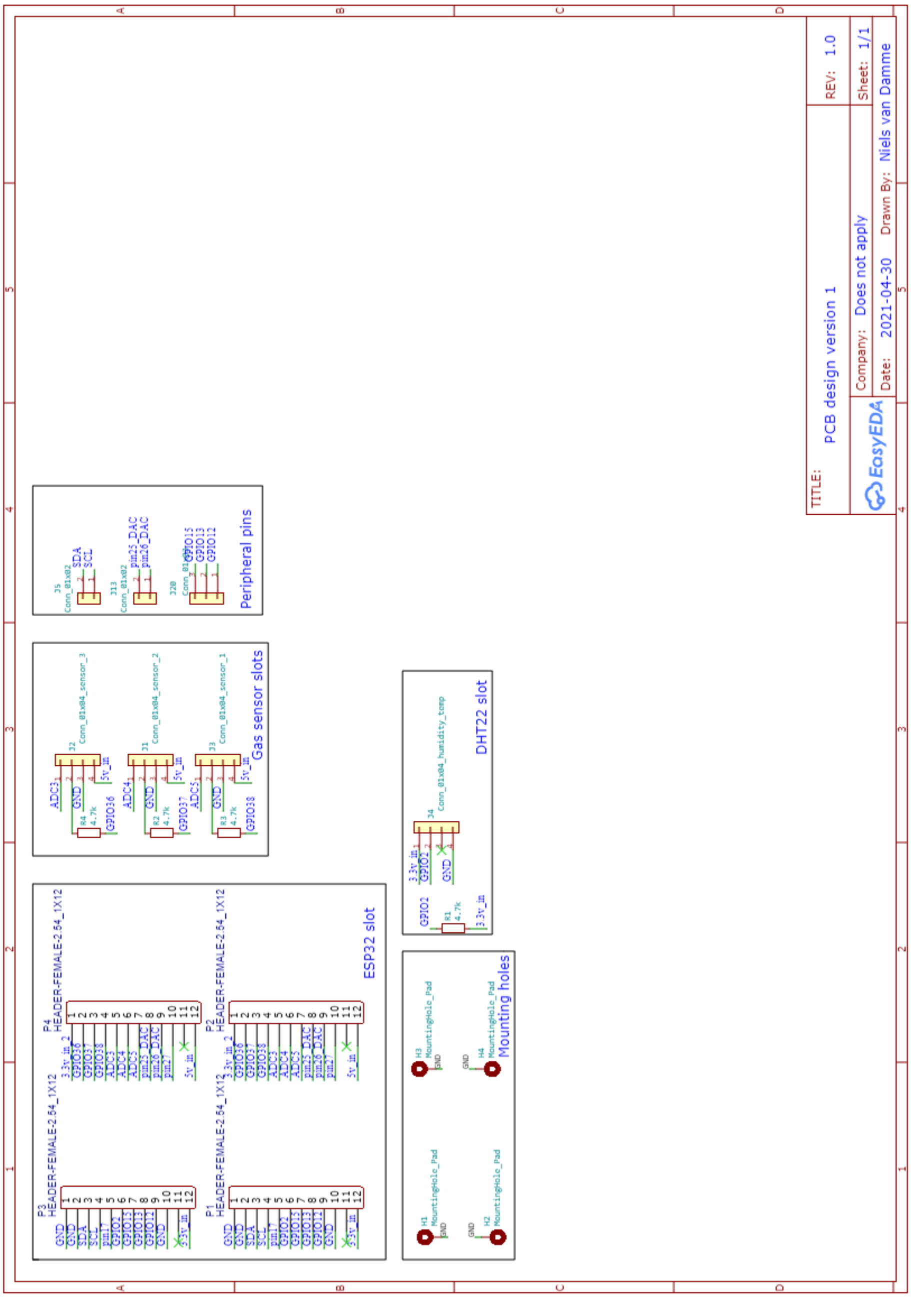


Figure F.1: The schematic of the first PCB design.

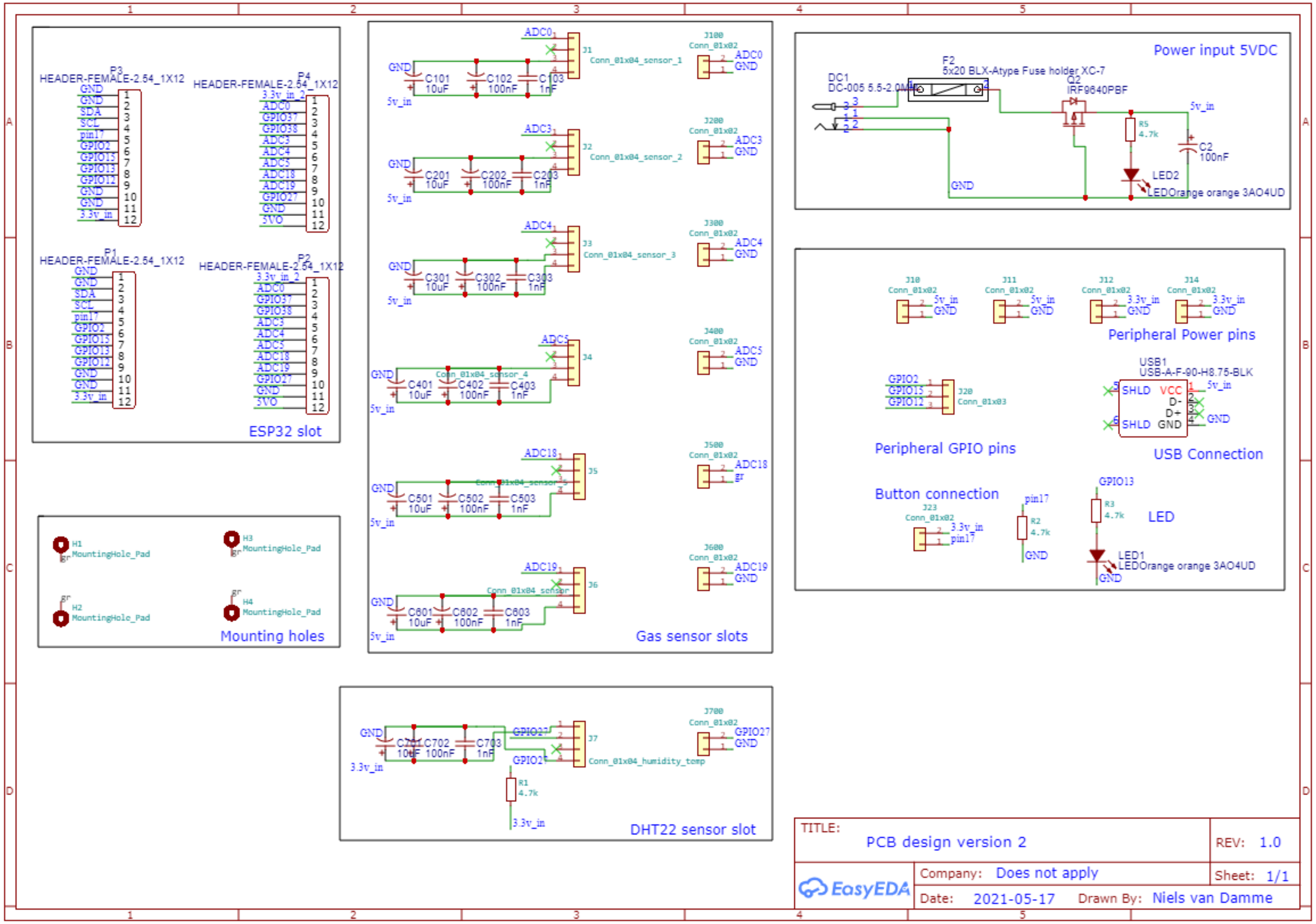


Figure F.2: The schematic of the second PCB design.

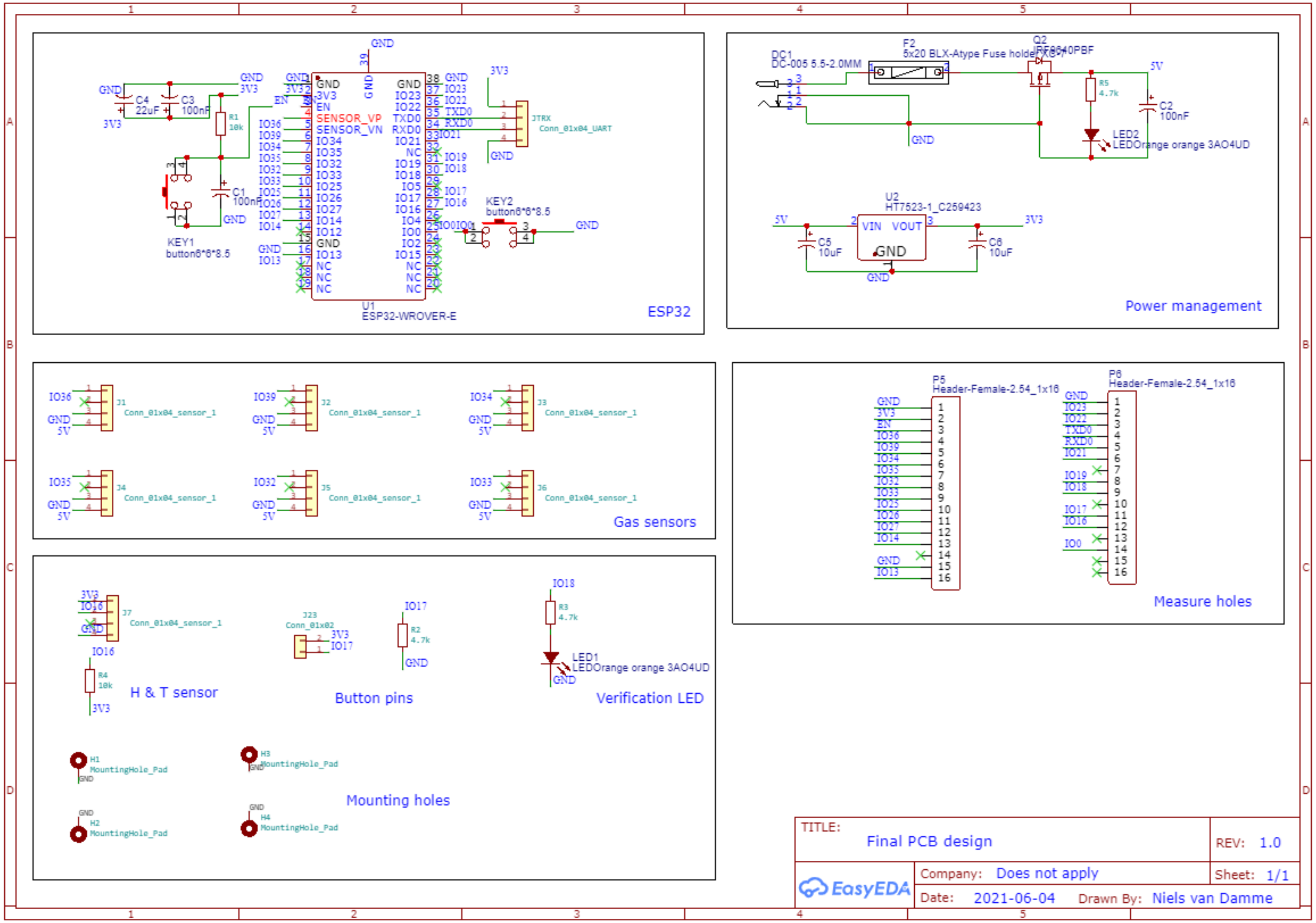


Figure F.3: The schematic of the third PCB design.

G

Code

This appendix contains the code used for modeling and plotting figures.

MQ Modeling

```python
# Modeling the output of MQ sensors with no gas present from temperature and humidity data (DHT22)
# Author: Daniel Stijns
import numpy as np
import matplotlib.pyplot as plt

# fit a
def linFit(data,sensor,plot=False,idx=0):
    # two models: one for temperature, one for relative humidity
    tempMod = np.polyfit(data['Temp'],data[sensor],1)
    RHMod = np.polyfit(data['RH'],data[sensor],1)

    # plot if wanted
    if(plot):

        # plot from temperature side
        if(idx > 0):
            plt.subplot(9,2,idx)
        predictor = np.poly1d(tempMod)
        tempPred = predictor(data['Temp'])
        # scale data from raw adc to mV
        plt.plot(data['Temp'][::10],data[sensor][::10]*1100/4096,'.')
        plt.plot(data['Temp'][::10],tempPred[::10]*1100/4096,'.')
        plt.xlabel('Temperature (Celcius)')
        plt.ylabel('Output Voltage (mV)')
        plt.title('Temp - '+sensor)
        if(idx <= 0):
            plt.show()


        # plot from relative humidity side
        predictor = np.poly1d(RHMod)
        tempPred = predictor(data['RH'])
        if(idx > 0):
            plt.subplot(9,2,idx+1)
        # scale data from raw adc to mV
        plt.plot(data['RH'][::10],data[sensor][::10]*1100/4096,'.')
        plt.plot(data['RH'][::10],tempPred[::10]*1100/4096,'.')
        plt.xlabel('Relative Humidity (%)')
        plt.ylabel('Output Voltage (mV)')
        plt.title('RH - '+sensor)
        if(idx <= 0):
            plt.show()
    return [tempMod, RHMod]
```

```

def bilinFit(data,sensor,plot=False,idx=0):
    # one bilinear model
    y=data[sensor] # data to fit against
    # matrix to fit with least squares
    # one column is filled with ones to act as a constant offset
    A = np.vstack([data['Temp'],data['RH'],np.ones(len(data['Temp']))]).T
    m1, m2, c = np.linalg.lstsq(A, y, rcond=None)[0]

    if(plot):

        if(idx > 0):
            plt.subplot(9,2,idx)
        tempPred = m1*data["Temp"]+m2*data["RH"]+c
        plt.plot(data['Temp'][::10],data[sensor][::10]*1100/4096,'.')
        plt.plot(data['Temp'][::10],tempPred[::10]*1100/4096,'.')
        plt.xlabel('Temperature (Celcius)')
        plt.ylabel('Output Voltage (mV)')
        plt.title('Temperature - '+sensor)
        if(idx <= 0):
            plt.show()


        if(idx > 0):
            plt.subplot(9,2,idx+1)
        tempPred = m1*data["Temp"]+m2*data["RH"]+c
        plt.plot(data['RH'][::10],data[sensor][::10]*1100/4096,'.')
        plt.plot(data['RH'][::10],tempPred[::10]*1100/4096,'.')
        plt.xlabel('Relative Humidity (%)')
        plt.ylabel('Output Voltage (mV)')
        plt.title('Relative Humidity - '+sensor)
        if(idx <= 0):
            plt.show()
    return [m1, m2, c]

# sensors under test
sensors = ['MQ-135','MQ-3','MQ-2','MQ-9','MQ-8','MQ-7','MQ-6','MQ-5','MQ-4']
# data to fit against, no modulation from chemicals is present
data = home_data

#dictionary of linear models
sepmodels = {};
plt.figure(figsize=(20,60))
for idx,i in enumerate(sensors):
    sepmodels[i]=(linFit(data,i,plot=True,idx=idx*2+1))
plt.suptitle('Do two linear systems predict sensor noise?')
# save the plot too
plt.savefig('lin.png')
plt.show()

#dicitionary of bilinear models
models = {};
plt.figure(figsize=(20,60))
for idx,i in enumerate(sensors):
    models[i]=(bilinFit(data,i,plot=True,idx=idx*2+1))
plt.suptitle('Does a bilinear system predict sensor noise?')
# save the plot too
plt.savefig('bilin.png')
plt.show()
```

Linear regression plots

```
% Name: Linear regression for the saturated salt solutions
% Description: This code generates from an array of X and Y points a linear
% regression line. Both the line formula as the R-number are printed.
% Author: Niels van Damme
% Version 1

%% sensor 1
%The datapoints
Y_long = [32.78 75.29 11.3 84.34]; %Y-Array with LiCl included
Y = [32.78 75.29 84.34];  %Y-Array with LiCl excluded
X_1_long = [36.29 73.67 18.32 81.34]; %X-Array with LiCl included
X_1 = [36.29 73.67 81.34];  %X-Array with LiCl excluded

%Plot the figure with LiCl included
figure(1)
scatter(X_1_long, Y_long);

%Set title and axis-labels
title('Linear regression model sensor 1');
xlabel('Ideal Relative Humidity (%)')
ylabel('Measured Relative Humidity (%)');

%Plot the figure with LiCl excluded
figure(2)
scatter(X_1, Y);

%Set title and axis-labels
title('Linear regression model sensor 1');
xlabel('Ideal Relative Humidity (%)')
ylabel('Measured Relative Humidity (%)');

%% sensor 2
X_2_long = [35.92 73.77 19.41 80.98]; %X-Array with LiCl included
X_2 = [35.92 73.77 80.98];  %X-array with LiCl excluded

%Plot the figure with LiCl included
figure(4)
scatter(X_2_long, Y_long);

%Set title and axis-labels
title('Linear regression model sensor 2');
xlabel('Ideal Relative Humidity (%)')
ylabel('Measured Relative Humidity (%)');

%Plot the figure with LiCl excluded
figure(5)
scatter(X_2, Y);

%Set title and axis-labels
title('Linear regression model sensor 2');
xlabel('Ideal Relative Humidity (%)')
ylabel('Measured Relative Humidity (%)');

%% sensor 3
```

```
%Data points for sensor 3
X_3 = [17.29 84.81];
Y_3 = [11.3 84.34];

%Plot the figure
figure(6)
scatter(X_3, Y_3);

%Set title and axis-labels
title('Linear regression model sensor 3');
xlabel('Ideal Relative Humidity (%)')
ylabel('Measured Relative Humidity (%)');

%% sensor 4
%Datapoints of sensor 4
X_4 = [74.63 18.92];
Y_4 = [75.29 11.3];

%Plot the figure
figure(7)
scatter(X_4, Y_4);

%Set title and axis-labels
title('Linear regression model sensor 4');
xlabel('Ideal Relative Humidity (%)')
ylabel('Measured Relative Humidity (%)');
```

Saturated salt solution plots

```
%Name: Saturated salt solution data import and plot
%Description: This code imports the data from a .txt file into an array.
%After, this array is plotted. Different sensors within the same salt
%solution environnement are plotted in the same plot. This code is specific
%for NaCl, but the same code has been used for KCl, MgCl and LiCl.
%Author: Niels van Damme
%Version 1

%% Sensor1 NaCl read file
%Imports the data from a .txt file
data_sensor1 = importdata('NaCL_sensor_1.txt'); % Gives cells for every line
fid1 = fopen('OutputFile.txt','w'); % open an output file
humidity_1 = data_sensor1(:,2); %Selects the humidity row (not temperature)
Size_sensor_1 = size(humidity_1,1); %Gives the lenght of the array
X_sensor_1 = Size_sensor_1*2; %Depending on datarate should be 2 sec or 8 sec
X_sensor_1 = linspace(1,X_sensor_1, Size_sensor_1); %Makes a correct X-array
Avg_1 = mean(humidity_1(1200:Size_sensor_1));
%Calculate the average of a specific part of the data

%% Sensor2 NaCl read file
%Imports the data from a .txt file
data_sensor2 = importdata('Sensor_2_NaCL.txt'); % Gives cells for every line
fid2 = fopen('OutputFile.txt','w'); % open an output file
humidity_2 = data_sensor2(:,2); %Selects the humidity row (not temperature)
Size_sensor_2 = size(humidity_2,1); %Gives the lenght of the array
X_sensor_2 = Size_sensor_2*2; %Depending on datarate should be 2 sec or 8 sec
X_sensor_2 = linspace(1,X_sensor_2, Size_sensor_2); %Makes a correct X-array
Avg_2 = mean(humidity_2(1500:Size_sensor_2));
%Calculate the average of a specific part of the data
```

```
%% Sensor blanko NaCl read file
%Imports the data from a .txt file
data_sensor3 = importdata('Blanko_Natrium_Chloride.txt'); % Gives cells for every line
fid3 = fopen('OutputFile.txt','w'); % open an output file
humidity_3 = data_sensor3(:,2); %Selects the humidity row (not temperature)
Size_sensor_3 = size(humidity_3,1); %Gives the lenght of the array
X_sensor_3 = Size_sensor_3*8; %Depending on datarate should be 2 sec or 8 sec
X_sensor_3 = linspace(1,X_sensor_3, Size_sensor_3); %Makes a corrext X-array
Avg_3 = mean(humidity_3(390:Size_sensor_3));
%Calculate the average of a specific part of the data

%% plot
%plots the values of the different sensors in one figure
figure(1)
plot1 = plot(X_sensor_1, humidity_1);
hold on;
plot2 = plot(X_sensor_2, humidity_2);
hold on;
plot3 = plot(X_sensor_3, humidity_3);

legend('Sensor 1','Sensor 2', 'Sensor 4');  %Legenda of the figure

%Set title and axis-labels
title('Relative Humidity (%) using NaCl for 3 sensors');
xlabel('Time (seconds)')
ylabel('Relative Humidity (%)');

%yline(33,'-','KCl ref');
yline(75.29,'-','NaCl ref');    %Reference line
%yline(85,'-','MgCl ref');
ylim([50 85]);  %Shows the right part of the y-axis
xlim([0,5200]); %Shows the right part of the x-axis
```