Bachelor Graduation Project

A Capacitive Implementation of an Online Sensor Grid for Measuring Grease Deposition in Extraction Channels

M. Verhoef, C. Martin

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Faculty of Electrical Engineering, Mathematics and Computer Science (EEMCS)
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Abstract

An extraction channel cleaning company wanted a grease thickness sensor to be developed that would send the data via the internet so that information on the thickness could be accessed remotely. This system consists of two parts: the sensor part and a communications part. This report is on the sensor part, which uses a change in capacitance of an interdigital capacitor, which in turn will change the frequency of the oscillator readout circuit. Initially research was done on the properties of grease to see if it would be a good method to measure the thickness. The results showed that it is possible to use capacitance, but that the permittivity of grease depends on the temperature, so the final design needs a temperature sensor. The prototype that was built was used to measure thicknesses and had quite reasonable results.

Preface

The project that is described in this report is part of the final project for the Bachelor Electrical Engineering of the Delft University of Technology students that was responsible for the design and production of a proof of concept. The goal of this project was to identify the most promising measurement method and strategy for real time monitoring of fat deposition in extraction channels. To test this method a sensor module with electronic readout and a communication module has to be designed.

The first weeks of the project were used to work on a literature study regarding the problem, the problem definition was defined, and the program of requirements was set up. After the research, the possible options for measuring methods were tested to see if they would be worth to be investigated more in-depth. As a result of these investigations it was possible to decide which methods were worth further research and implementation. It was decided that there were two different measurement implementations that showed promise and that these would be researched further. At this point in time, after the first three weeks, the project group was split into three subgroups: a group that would look for an acoustic implementation of the sensor, a group that would investigate a capacitive implementation of the sensor, and a group that would be responsible for the communication module and system design of the project.

We would like to thank our supervisors Andre Bossche and Jeroen Bastemeijer for the guidance, advice and support throughout the project. Also we would like to thank Michael and Dave from VETkanaal for their contributions to the project and the submission of the Bachelor Graduation proposal. Finally we would like to thank the Delft University of Technology for the available resources put at our disposal for working on this project.

Contents

Introduction

The origin of the subject of this thesis lies in simple cooking. When you cook, you are likely to use some kind of fat or oil. Whether it is baking something in a pan to prevent your food from burning or to give it a nice crunchy layer, deep-frying chips and snacks or cooking pasta with a dash of olive oil in the water, the steam coming off the food will contain small greasy particles. Usually this air is sucked into an extraction channel and exhausted outside.

Some of these particles however, while flowing through the duct, will precipitate and stick onto the walls and form a greasy film. For a normal household, this will not cause any problems, because the amounts of prepared food are relatively small. For a catering business though, the layer can build up faster and become quite substantial. This poses a serious fire hazard, because it can catch fire. So the channels should be cleaned on a regular basis, or when the thickness exceeds a certain value.

Figure 1-1: A comparison of an extraction channel before and after it is cleaned **vetkanaal**

1-1 Problem definition

The measurement of the thickness nowadays is still done by hand, for example by using an Elcometer [1]. This costs a lot of time, because an employee has to be at the location, and that is why the extraction channel cleaning company "VETkanaal [2]" asked us to develop a sensor that can measure the thickness of the grease without being operated by a person and send the data over the internet so that the channel can be monitored at any place.

In the Netherlands there are currently no legal regulations for channel cleaning, but insurance companies can force catering companies to get their extraction channels cleaned regularly through personalized policies (depending on the size of the company) [3]. To know whether a channel needs to be cleaned or not, the thickness of the layer of grease is measured.

Measurements conducted by VETkanaal in the past were done by means of a 'meetkam' (measuring comb) [4]. After that they measured it digitally, with an Elcometer. This is the method is currently used, but it costs a lot of human resources. Instead of sending someone to measure the thickness, a system was requested by VETkanaal that measures the thickness of the grease layer using sensors and sends this data over the internet so that the information can be remotely accessed by VETkanaal and the catering company. That is the project, for which our subgroup developed a capacitive sensor.

1-2 Outline

This report will start off with the program of requirements in Chapter 2. After that the theory behind the sensor system will be explained. The method of measuring, system overview and theory of the capacitive implementation can be found in Chapter 3. Next up, in Chapter 4 are the preliminary measurements, the results of which are discussed there. The preliminary measurements have their own discussion and conclusion, so that the focus of the discussion, Chapter 6, and conclusion, Chapter 7, will be all about the prototype. In the following Chapter 5 the design of the prototype and results of measurements with it are discussed. In between the preliminary measurements and the discussion is Chapter 5, containing the design of the prototype and the results that were achieved with it. The final Chapter 8 contains some final remarks.

Program of requirements

2-1 Introduction

This chapter lists the requirements that were deducted from the information from VETkanaal about their needs and those of other stakeholders.

2-2 General

- The sensor should be independent of orientation, length and shape of the extraction channel. The cross section of the channel is at least 12.5 cm.
- The measurement results should be independent of the temperature.
- The sensor should work properly up to an internal temperature of the duct of 100 degrees and down to 20 degrees.
- The measurement results of the sensor should be independent of the different types of material which are used for the extraction channels.
- The consistency of grease deposit differs per site and per extraction channel. The sensor should work for every form of grease deposit.
- The cleaning of the extraction channels happens with with highly alkaline chemicals; the design has to be able to either withstand or not get in contact with these chemicals.
- In order to be able to maintain the design by the current cleaning crew, the maintenance of the design should be simplistic in such a way that it can be performed by anyone who was not involved in the design process.
- The sensor should be able to measure and quantify the thickness of grease in an extraction channel.
- The sensor should quantify at least a level where the thickness is considered dangerous. Usually a level of 500 μm is considered dangerous.
- The sensor should have a lifetime of at least one year (the sensor should be working until the next time of cleaning).

- The range interest, in which the sensor is able to measure accurately, is from 0 μm to 600 μm.
- Within the range of interest the accuracy of the measurement results should be within ± 30 μm .
- The maximum distance between two sensors is 100 meters. The minimum distance is 1 meter.
- The sensor design should differ from the already existing patent on grease measurement [5].
- The responsibility for the time to clean the extraction channel will be at the cleaning company.
- The sensor should not influence the even grease deposition in the extraction channel.

2-3 Sensor

- The sensor should quantify at least a level where the thickness is considered dangerous. Usually a level of 500 μm is considered dangerous.

2-4 System Design

- Up to a maximum of 8 sensor per system can be used.
- The measurement results should be displayed on an online platform.
- The production cost should be in in line with the cost of an extraction channel.

2-5 Laws and Ethics

- The sensor design should differ from the already existing patent on grease measurement [5].
- The responsibility for the time to clean the extraction channel will be at the cleaning company.

Theoretical Background

3-1 Introduction

This chapter contains the methods encountered during the search for a measurement principle for the sensor and the justification of the methods that were chosen. After that, the theory necessary to do research into the capacitive measurement method and to build a prototype is explained.

3-2 Measurement Methods

The very first step in this project was doing research on which methods are currently used or could be used to measure a layer of any material, not only grease and not only very thin layers. Out of all these options a decision was made on the basis of criteria such as cost and maintenance, which will be listed later on in this section.

There are many sensors that use principles of optics to measure thickness or fat. For example ellipsometry [6] [7] [8] [9]. Another method that makes use of optics is with infrared or near-infrared, for example to measure fat in food or human bodies [10] [11]. Using the opacity of grease could also be a possibility [12]. As a matter of fact, it is already used in a patented thickness measurement system [5].

Making use of optics however, could be hard to implement as it requires an antenna and a receiver. Since the sensor has to work in all kinds of shapes of ducts, this is a clear drawback.

A second possibility is using acoustic properties of materials. Grease or other layers will affect the speed of sound, the resonance frequency and decay of signals in channels. Acoustic methods are already being used to determine fouling layers, oil thicknesses in pipelines and body fat as well [13] [14] [15].

Thirdly, one could use change in inductance [16], capacitance [17] or conductance [18]. Standing out is the capacitive method, since the other methods are more affected by the fact that there is a metal duct.

A fourth possibility could involve measure using electromagnetic radiation [19] [1]. This is quite complex and requires a setup that is hard to make in an extraction duct.

Another option is using thermal measurements. By knowing the temperature inside the channel and the temperature outside the channel, the thickness of a grease layer could be determined [20] [14].

Out of all these options, a decision was made on the basis of cost, maintenance, complexity, accuracy, invasiveness, testability and dependency on the surroundings. Two methods were chosen: acoustic and capacitive.

3-3 Capacitive Measurement

Once the method was chosen, some knowledge about capacitances is required in order to explain why it works and what needs to be researched more in order to be able to build a prototype. The simplest formula for capacitance is [21]:

$$C = \frac{q}{V} \tag{3-1}$$

This is an important equation, because it shows that the capacitance depends on the voltage between two electrodes of a capacitor. Dielectric materials are non-conducting materials, which, if placed between the electrodes, decrease the electric field. The molecules of dielectric materials in an electric field are polarized in such a way that the polarization counteracts the electric field between the electrodes. The diminished electric field leads to a decreased voltage. This will lead to an increased capacitance. This is the principle that will be used by the sensor.

The amount by which the capacitance will be increased depends on the physical properties of the grease, the relative permittivity e_r in particular. The relative permittivty should be high enough to be able to measure a difference. The easiest way to determine the permittivity of a material is by using a parallel plate capacitor. For a parallel plate capacitor, equation 3-1 can be written in the form:

$$C = \frac{\epsilon_r \epsilon_0 A}{d} \tag{3-2}$$

With A the area of the parallel plates, d the distance between them and e_0 the permittivity of vacuum (8.85 F/m [21]) Though so elegant in its simplicity, a parallel plate capacitor will not be very practical to implement in an extraction channel. If the plates were to be placed across from each other in the channel, the distance d in equation 3-2 between the two plates would be at least 12.5 cm (see program of requirements 2) and the capacitance would be incredibly small. If the plates were to be placed at a reasonable distance from each other, this would mean that one of the plates would stick out in the channel, and would influence the grease deposition and the measurement would not be accurate. The implementation will consequently make use of an interdigital capacitor.

3-3-1 Interdigital Capacitor

The interdigital capacitor is a more complex capacitor. Figure 3-1 shows the electrical field in the interdigital capacitor. In this picture it can be seen how the field lines go through the grease layer. More in depth explanation about how the change in capacitance is measured will be done in Chapter 5.

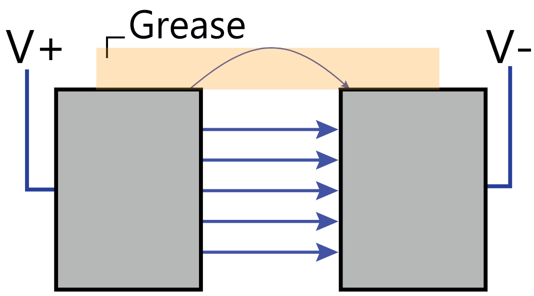


Figure 3-1: Cross section of interdigital capacitor with two fingers with field lines of the electrical field indicated by the blue arrows.

The structure with all of the electrodes makes the calculation of the exact capacitance much more complex than the formula for the parallel plates. The equation, belonging to the equivalent circuit of an interdigital capacitor, shown in figure 3-2 is [22]:

$$C = (N-3)\frac{C_1}{2} + 2\frac{C_1 C_E}{C_1 + C_E}, N > 3 \tag{3-3}$$

With N the number of electrodes. The formulas for C_1 and C_E are quite complex and out of the scope for this thesis, but can be found in [22].

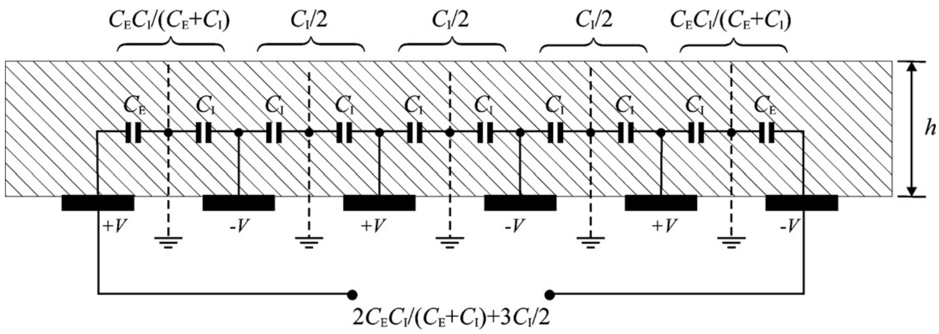


Figure 3-2: Equivalent circuit of an interdigital capacitor [22].

One other thing to look into during the research is the temperature dependency, as the temperature will range between 20°C and 100°C.

3-4 Complete system

For the sensing system will only be a part of a larger system , figure 3-3 shows a schemtatic of what the system as a whole will look like.

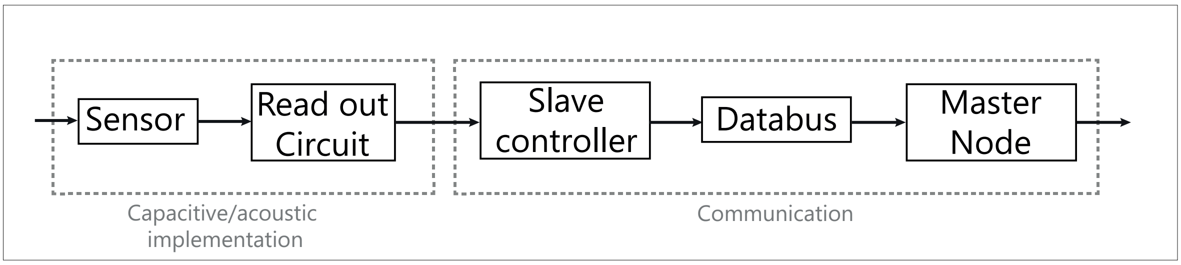


Figure 3-3: Global design of the whole sensor system

The first part is the sensor with its readout circuit, which is the part that will be discussed in detail in the next chapters. One other group works on a sensor too, an acoustic one. The second part is the data transfer from the sensors to the internet. They will not be discussed any further.

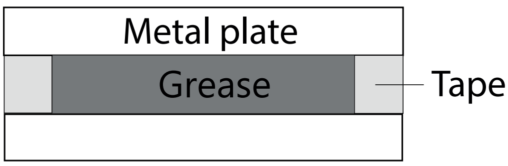
Preliminary Measurements

4-1 Introduction

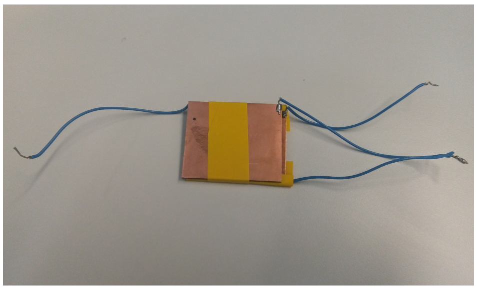
In this chapter the results of measurements conducted to establish knowledge about the properties of grease are described. All capacitance measurements were done with a Digimess RLC meter 200 [23] with the following settings: 1V and 1kHz. The resolution was 0.1 pF. For the temperature measurements a digital multimeter was used and an infrared thermometer, of which the resolutions were 1 °C and 0.1 °C. There were three types of grease used during the measurements: butter, deep-frying fat and extraction channel grease samples obtained from VETkanaal.

4-2 Measurement

As mentioned in Chapter 3, the first measurements were done using a parallel plate capacitor. The plates consisted of two metal plates with a layer of FR4 in between them, each having a total thickness of 1.6 mm. Figure 4-1a and figure 4-1b show the capacitor. In order to measure the capacitance, the upper copper layer of the top plate and the lower layer of the bottom plate were grounded while measuring.



(a) First parallel plate capacitor: model



(b) First parallel plate capacitor: picture

Figure 4-1: First parallel plate capacitor.

To check if the capacitor was working according to formula 3-2, the first measurements were conducted with air as a dielectric. Because all of the variables in that formula were known, besides measuring the capacitance could also be calculated. Figure 4-2 shows the measurements and theoretical values for different thicknesses of the fat layer. As a spacer, 1 to 5 layers of 3M Temflex 1500 Vinyl Tape was used. It has a thickness of about 120 μm [24], so that the measurement range of up to 600 μm was covered by the measurements.

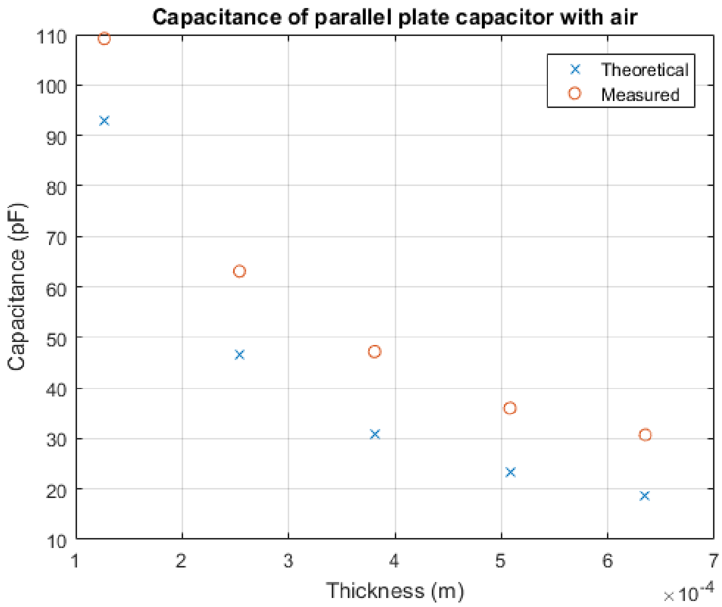


Figure 4-2: First parallel plate capacitor: no grease. Difference in theoretical and measured can be subtracted from measured capacitance with butter.

Looking at figure 4-2, the capacitor seems to have some kind of offset. This could be caused by the cables or influence from the surroundings. Further the measured and theoretical graphs look quite similar.

After the measurements with air, measurements with butter were conducted. Besides the fact that up to this point the tape was the way to measure thickness, To have an equally thick layer everywhere, the tape would also prevent the butter from leaking off the plate because the butter was runny from being heated up with a hair dryer to get an equal layer. After the butter was applied on the bottom plate, the second plate was pushed onto the tape layer to squeeze out the superfluous butter to make sure that there were no air pockets inside. For this measurement too thicknesses of up to 5 layers of tape were used, three measurements of each distance. The results can be seen in figure 4-3.

The goal of these measurements was to determine the relative permittivity of the butter, but figure 4-3 shows that the measurements are not very precise. The relative permittivity calculated with the data varied between 2.3 and 4.8. Because more butter than necessary is applied to avoid air pockets, some of the butter might form a layer between the tape and the upper plate. The tape is flexible too. When more pressure is applied, the tape will be thinner. So taking tape as a measure of thickness is far from ideal.

Consequently, a second parallel plate capacitor was built, as can be seen in figures 4-4a and 4-4b. The distance between the plates is determined by plastic rings with a thickness of 0.5 mm. Measurements with this capacitor were done with deep-frying fat which has a fat

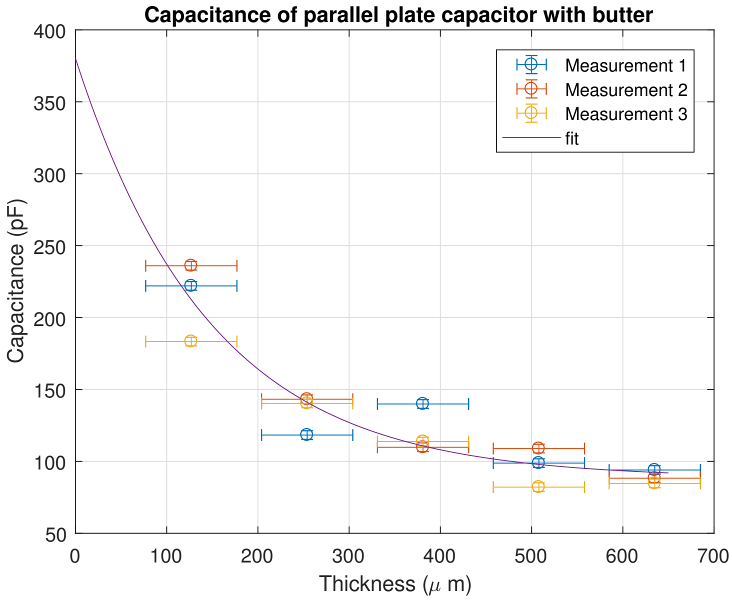
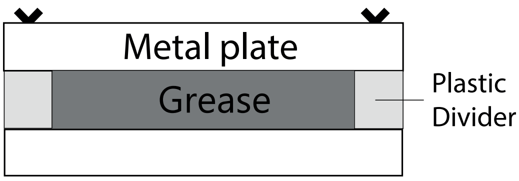


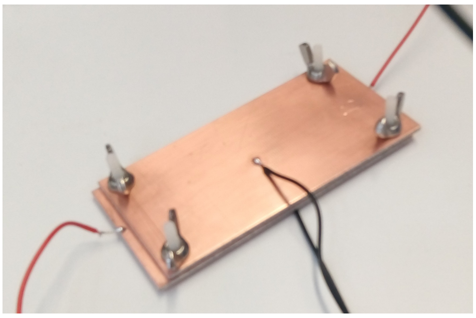
Figure 4-3: First parallel plate capacitor: dairy butter was used in these measurements which has a fat percentage of 82%

percentage of 100 %. At this point it was decided that all of the measurements would be with deep-frying oil, because it is easier to work with. Because the distance between the plates was fixed, this capacitor was used to see if the temperature influences the capacitance. Results can be seen in figure 4-5.

There were two capacitors used to measure the temperature influence, hence measurement 1 and measurement 2. Although there are not many measurements, it is clear that the capacitance is higher when the temperature is higher. The difference between the two measurements might be explained by the fact that the thickness depends on how high tight the butterfly nuts are tightened. In the middle there might also have been some additional fat, because the pressure is applied on the corners, and not in the middle.



(a) Second parallel plate capacitor: model



(b) Second parallel plate capacitor: picture

Figure 4-4: Second parallel plate capacitor.

After the measurements with the second parallel plate capacitor, it was time to start measuring with an interdigital capacitor, since that was the one going to be implemented. This

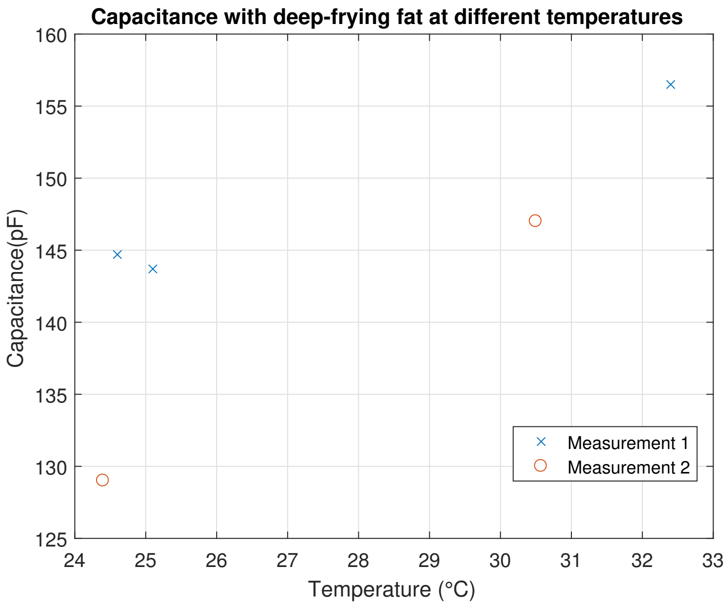
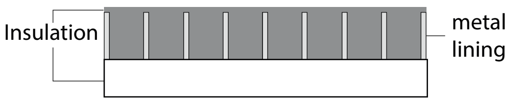
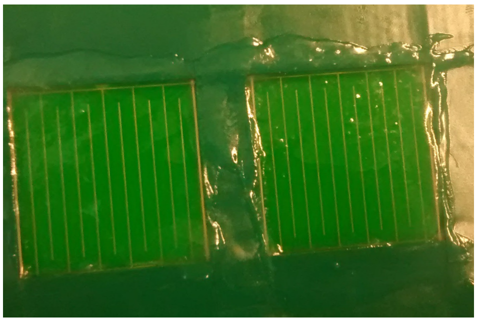


Figure 4-5: Second parallel plate capacitor: temperature dependence

capacitor is shown in figures 4-6a and 4-6b. The capacitance of this capacitor was about 3 pF without any grease on it. The size of the whole structure was 3 by 3 cm and contained 12 electrodes. The soldering mask on this capacitor functions as an insulation layer. As can be seen on picture 4-6b, of this capacitor there were also two, capacitor A and capacitor B in figure 4-7.



(a) First interdigital capacitor: model



(b) First interdigital capacitor: picture

Figure 4-6: First interdigital capacitor.

These results show that with an interdigital capacitor, capacitance changes could be measured as well. The results are not so precise again, because thickness was measured with 1 to 3 layers of tape. The capacitance of the capacitor was quite small, and changes to be measured would be too, so another interdigital capacitor was designed. The second interdigital capacitor was larger and supposed to have a larger capacitance. This capacitor is shown in figures 4-8a and 4-8b. It was made by hand so measures were not that accurate The fingers were about 3 mm and the spacing was about 0.5 mm. This capacitor was 6 cm by 6 cm, contained 14 electrodes and had a capacitance of 17.3 pF without fat. The capacitance measurements are

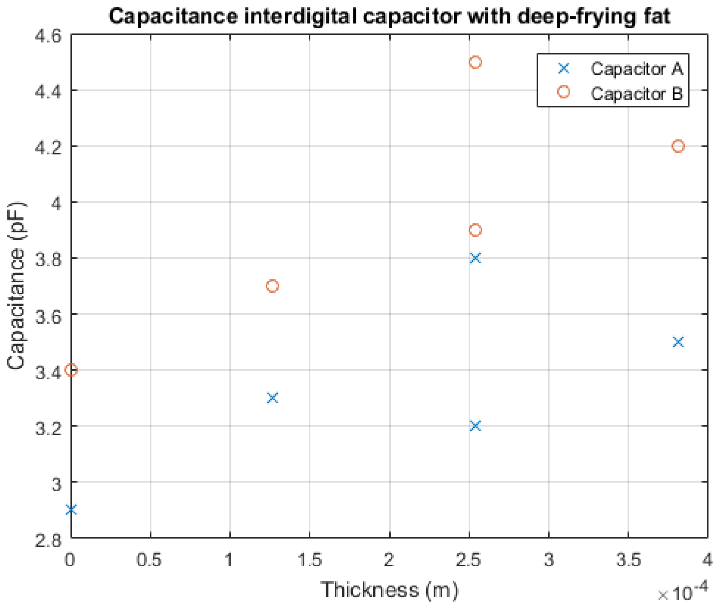
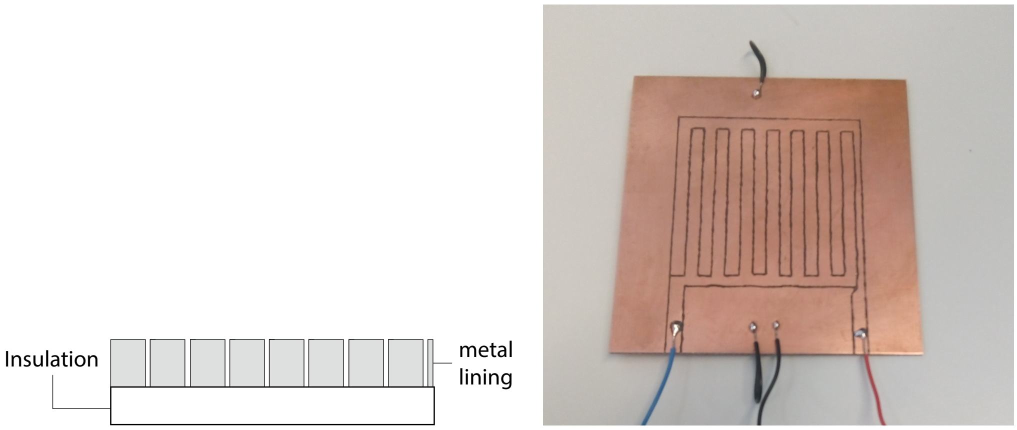


Figure 4-7: First interdigital capacitor: capacitance changes with thickness of grease layer

shown in figure 4-9. The capacitance seems to increase linearly with the thickness, but at some point this linearity stops and the capacitance does not increase anymore. A wider space between the electrodes could solve this problem [25]. There were also some final temperature measurements done using this capacitor. In order to do so, hot melted deep-frying fat was poured onto the capacitor. Measurements were conducted during the cooling down of the fat. This was done 3 times and the results are plotted in figure 4-10.

There were no elaborate measurements with the extraction channel grease samples, however there was a quick test if the capacitance change would be similar. Apparently the samples contain conducting particles, because the capacitance of the second capacitor vanished with the grease on it. Measurements with the second parallel plate capacitor insulated with cling film suggested that the relative permittivity is much higher than that of deep-frying fat.



(a) Second interdigital capacitor: model **(b)** Second interdigital capacitor: picture

Figure 4-8: Second interdigital capacitor.

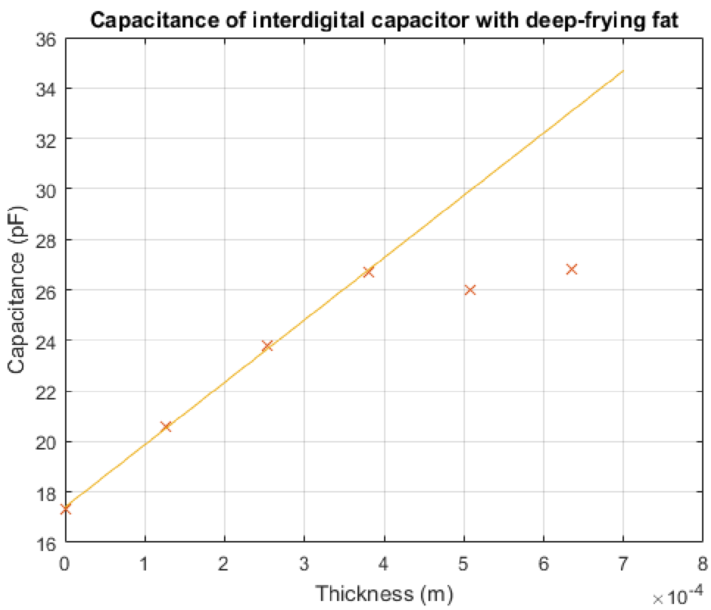


Figure 4-9: Second interdigital capacitor: thickness measurement

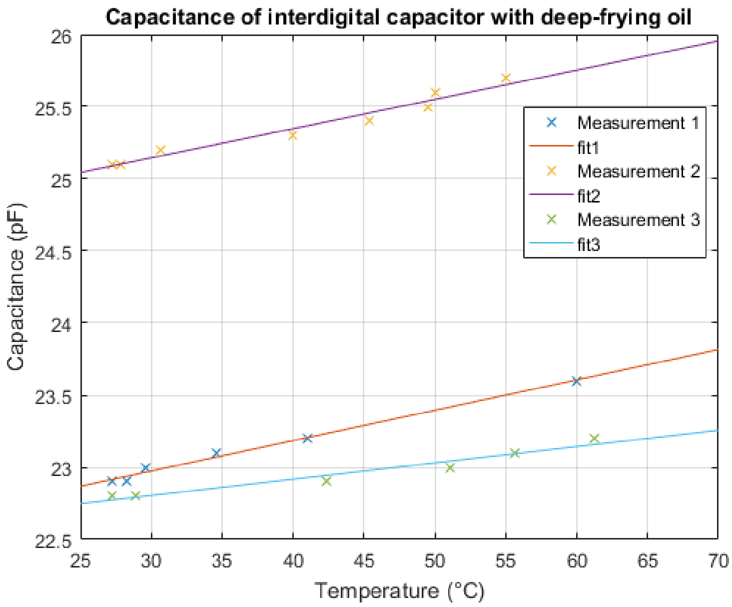


Figure 4-10: Second interdigital capacitor: temperature dependence

4-3 Discussion

As can be seen in the results of the first parallel plate capacitor (in figure 4-3), the capacitance for the same thickness of the grease layer varied up to 60 pF. This was too much of a difference on a scale of 200 pF to assign a capacitance to a thickness. The variance could possibly be explained by two major factors: temperature of the butter/capacitor and the inconsistency with the layer thickness.

In the results of the second capacitor, which was less dependent of different distances between the plates and had a temperature measurement, it can be seen that the temperature of the fat definitely has an effect on the capacitance (see figure 4-11). So this could explain the inconsistent values of previous measurements (since the fat was heated and cooled down, but probably measured at different temperatures). Figure 4-11 shows the effect of temperature on the permittivity of deep-frying fat. These measurements however, seem to be only qualitative and not quantitative themselves. Again the measurement method is not precise enough.

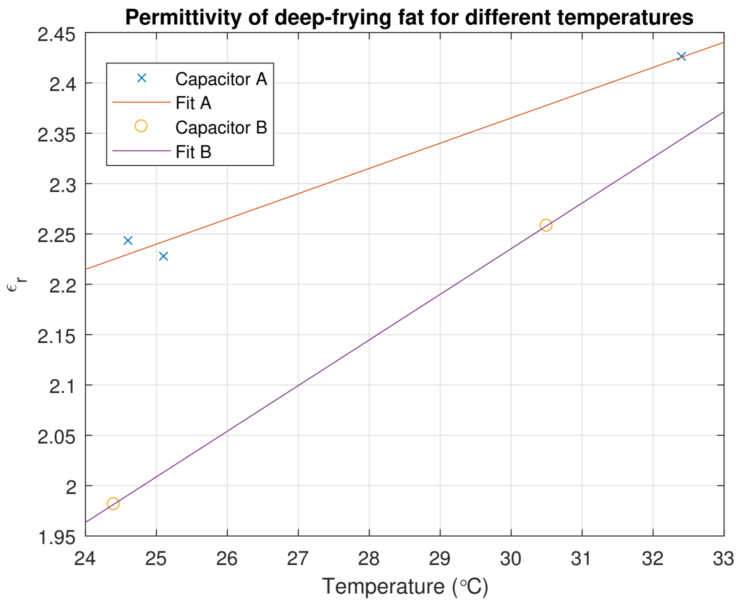


Figure 4-11: ϵ_r of grease with the second parallel plate capacitor. It is dependent on the temperature.

This second parallel capacitor was expected to have less variance in thickness measurements, but did not cancel it at all. The formula to calculate the capacitance of an interdigital is quite complex too, so even with the permittivity of deep-frying fat, it would be hard to design a perfect capacitor. The idea to determine once and for all the permittivity of deep-frying fat and other types of grease was abandoned, because there was enough knowledge gathered during the measurements to go ahead and design a prototype.

One other advantage of the interdigital capacitive measurements was that the fat was visible during the measurements. Temperature measurements for the parallel plate capacitor were not so easy, because there is only a small area on the sides where you can point the infrared thermometer at, possibly resulting in the measurement of the surroundings as well.

There were hardly any measurements with extraction channel grease samples. Some quick tests though showed that the measurement principle should still be applicable.

4-4 Conclusion

Although the permittivity of deep-frying fat was not established, some important conclusions can be drawn from all of the measurements. First of all, the method seems to be suitable to measure layers of grease. The change in capacitance is large enough to be measured.

Things to consider during the design are the temperature dependency. If the system has to measure the thickness in temperatures ranging from 20°C to 100°C, there needs to be an adjustment for the temperature. A temperature sensor should be included in the design.

The interdigital capacitor will need an insulation layer. This is not necessary when measuring deep-frying fat, but it will be for extraction channel grease. The layout of the capacitor can be similar to the second interdigital capacitor, but with wider spacing between the electrodes.

Prototype

5-1 Introduction

As written in Chapter 1, VETkanaal cleans the channels. For the first time cleaning, holes are sawn in the ducts. These holes are afterwards closed with small doors, so that the holes can be used for future cleaning too. When the channels are being cleaned, the doors are removed. This has led to the choice to place the sensor inside of the door and the readout circuit outside of the door so that the grease layer will only build on the capacitor and temperature sensor and not on the other electronics involved and the chemicals used during cleaning will not touch any components. An elaborate description of the other design choices made in the process of designing a prototype can be found in this chapter.

5-2 Design

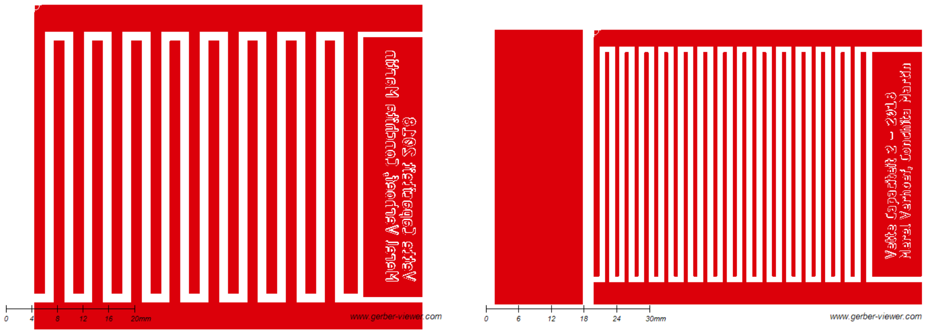
The conclusions drawn from the preliminary measurements were mainly that the method of measuring the capacitance to determine the thickness of the grease layer could quite well be used, but there are some things to be reckoned with. The capacitance of the grease depends on the temperature of it, so a temperature sensor is needed, to be able to determine the thickness of the layer. Also the interdigital capacitor needs an insulation layer on top of it, because the grease turned out to contain some conducting particles, resulting in no capacitance at all, when the electrodes were not insulated.

Then there were constraints from the communications group. The maximum frequency that can be measured with an Arduino Uno was said to be 50 kHz an the input signal should not have a voltage higher than 5V.

5-2-1 Capacitance Measurement

The results of the measurements with the second interdigital capacitor showed that with a capacitor like that, the change in capacitance with a layer of grease was quite clear, the difference between no grease and a layer of about 500 μm being 8.7 pF, an increase of 50%. That is why a comparable capacitor was the capacitor of choice.

Initially, the design was like figure 5-1a. It has 1.5 mm wide fingers, with a spacing of also 1.5 mm. The spacing between the electrodes is larger, because the grease layer to be measured is



(a) First capacitor design **(b)** Final capacitor design

Figure 5-1

thicker than could be measured with the one used for the earlier measurements. The larger spacing would result in a lower capacitance, so more fingers were used.

This first design was problematic in several ways. The capacitance was lower than expected, namely 6.4 pF. With the circuit where it was going to be used already in mind, this would result in the use of undesirably high value resistors. It also appeared that with the Elcometer[1] it was impossible to measure the grease thickness, because there is no big enough copper area where it could be applied. Measurements on the narrow fingers resulted in unreliable results.

The second design, figure 5-1b, was improved according to the findings of the first one. The spacing between the fingers was decreased tot 1.2 mm, the number of fingers was increased, and an area where the grease thickness could be measured was added to the design. This second design had a capacitance of 11.2 pF without insulation and 12.6 pF with one layer of self-adhesive book cover film as a means of insulation. This value resulted in acceptable component values.

So with the capacitor as the sensor, the readout circuit could be designed. Because the change in capacitance was expected to be considerable, a differential circuit was considered to not be needed. Instead an oscillator circuit producing a square wave was used, with an LM555 oscillator. The frequency of this oscillator is determined by the capacitance of the interdigital capacitor and two resistors [26]:

$$f = \frac{1.44}{(R_a + 2R_b)C} \tag{5-1}$$

The duty cycle only depends on the ratio between R_a and R_b:

$$D = \frac{R_b}{R_a + 2R_b} \tag{5-2}$$

For a duty cycle of about 50% R_b should be much larger than R_a. The duty cycle is not of particular interest, but nonetheless R_a was chosen much lower than R_b. With a maximum frequency of 50 kHz the minimum value of R_b was calculated with formula 5-1. R_a can be neglected, because it is set to be very small compared to R_b. With a capacitance of 12.6 pF this yielded a value of at least 1.14 MΩ, so a 1.2 MΩ resistor was chosen. As for R_a 1 kΩ was chosen, resulting in a duty cycle of almost 50%.

The design of the circuit further consists of a 10 nF decoupling capacitor, required because port 5 is not used. The complete design can be seen in 5-2. The resistor after the output is to reduce the current to the Arduino. Using formula 5-1 again, this circuit should have a frequency of 48.6 kHz. The capacitance will increase with a layer of grease, so the frequency will become lower, thus never exceeds 50 kHz.

Considerations towards the power supply came from the output signal of the LM555 oscillator. The high output voltage is about the same as the source voltage. So, if possible, the LM555 should not be powered with more than 5V.

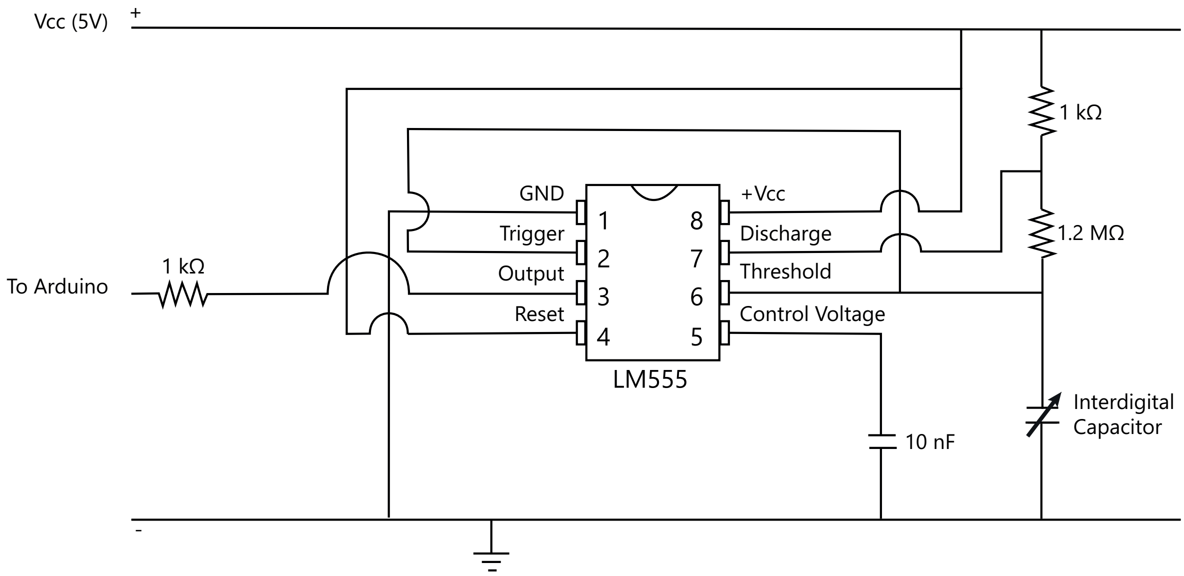


Figure 5-2: Oscillator circuit layout.

5-2-2 Temperature Measurement

The second part of the sensing subsystem is the temperature sensor. A popular temperature sensor is the LM35. It has a range from -50°C up to +150°C [27], which is suitable for the temperatures to be measured are expected to be between 20°C and 100°C. It can be operated with a single supply of 4-30V. Considering the maximum source voltage of 5V for the oscillator, this narrows down the supply voltage to 4-5V.

The LM35 generates an output voltage of 10 mV per degree Celcius. A range of 20°C to 100°C will accordingly lead to outputs of 0.2-1V. As mentioned before, the maximum input voltage of an Arduino Uno is 5V, so the temperature sensor signal could easily be amplified about 4 times.

Many operational amplifiers use voltage supplies of +15V and -15V, but if possible, the op amp used here should work fine with a single supply of 4-5V. The op amp chosen was the TLV2371, which is rated from 2.7 up to 16V [28]. For the non-inverting amplification of about 4 times, resistors of 1 kΩ and 3.3 kΩ were chosen, yielding a gain of 4.3 times, because for the non-inverting configuration the following formula applies:

$$V_{out} = V_{in}\left(1 + \frac{R_F}{R_G}\right) \tag{5-3}$$

As with the oscillator circuit, a 1 kΩ resistor was placed in series with the output to limit the current into the Arduino. The schematic can be seen in figure 5-3.

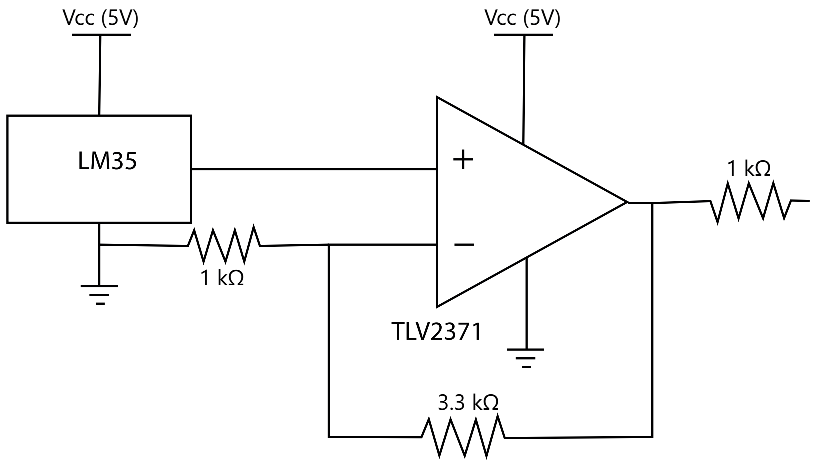


Figure 5-3: Temperature sensor circuit.

As it turned out, the Arduino has a +5V output pin, so this pin can perfectly be used as a power supply for both the LM555 timer as the temperature sensor with amplification.

5-3 Measurements

With the circuit the design completed, the next step was to build it and test it.

5-3-1 Building the Circuit

First, the temperature sensor circuit was built and tested. One measurement with the digital multimeter at the output of the LM35 showed a voltage of 261 mV, and at the output of the amplifier 1.126 V, which is an amplification of 4.3 times, so that part was working fine. At 10 mV per degree Celsius, 261 mV corresponds to 26°C, for which it was estimated that that could quite well be true.

Subsequently, the oscillator circuit was built. The frequency the oscilloscope showed was nowhere near the expected 48.6 kHz. It was 13.2596 kHz. Using formula 5-1, the capacitance of the interdigital capacitor appeared to be 45.2 pF. As it turned out, this was the case because one electrode of the capacitor was grounded. Because the capacitor consists of 2 copper plates with FR4 in between them, where the bottom plate was grounded too, the capacitance between one of the electrodes and the grounded copper plate was also measured in the circuit shown in 5-2. With a ground at one of the pins in figure 5-4, the capacitance of the interdigital capacitor and the parallel plate capacitance of the bottom copper plate and the non-grounded electrode were put in a parallel configuration, thus adding up.

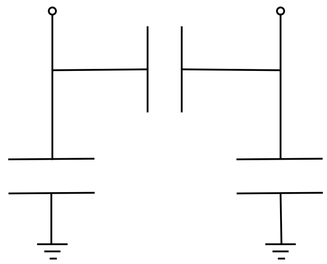


Figure 5-4: Model of the interdigital capacitor. The middle capacitance is due to the interdigital capacitance, the outer two are each due to one of the electrodes being a parallel plate capacitor with the bottom copper plate with FR4 in between.

Both capacitances were measured; yielding 12.4 pF for the interdigital structure, and 32.5 pF for the parallel plate. Together this is 44.9 pF, about the with the frequency calculated 45.2 pF. So the oscillator circuit was operating as expected too. The larger capacitance was not considered to be a problem. The square wave at the output has a peak-to-peak voltage of 4.8V, which is good enough for the Arduino to measure the frequency. The square wave produced by the oscillator with no grease on the capacitor is shown in figure 5-5

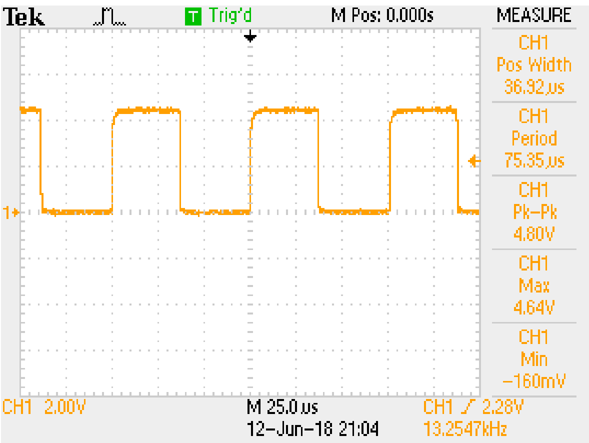


Figure 5-5: Screenshot of a measurement with the oscilloscope with no grease layer on the sensor.

The system was connected to an Arduino Uno to test if the output signals of the sensors could be measured with it, which was the case. The Arduino was able to power the sensors with its 5V output pin, no external voltage source was needed and the data was displayed on a computer monitor. So with the use of a computer the system as a whole was functioning. A picture can be seen in figure 5-6. Code to read out the temperature can be found in Appendix A-4.

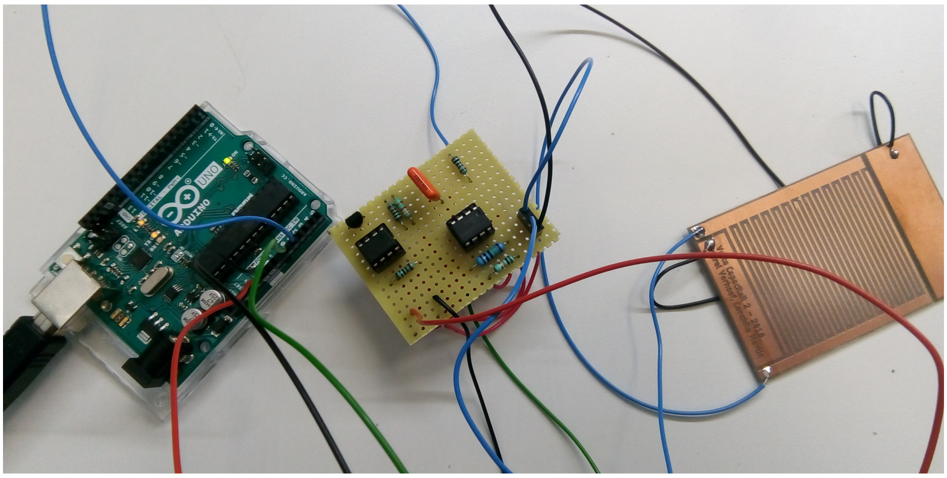


Figure 5-6: All components connected.

5-3-2 Calibration of the Sensor

To measure the thickness of the grease layer, it is not important to know the change in capacitance. Knowing the change in frequency is enough, because one is directly related to the other. So from this point, measurements were conducted to find out the relation between frequency and layer thickness.

Like earlier measurements, these measurements were also conducted with deep-frying fat that was melted and poured onto the capacitor to try to get an as even as possible layer of fat. After it congealed and the temperature had become stable, the frequency of the oscillator was measured. This was done with an oscilloscope (Tektronix TDS 2022C) and with the Arduino. The temperature was also measured with the sensor, but in this case that information was not very important, as the temperature of the air did not change very much.

Figure 5-7 shows the results of the measurements. The accuracy of the thickness measurements with the Elcometer is questionable though. The points plotted are the averages of 11 up to 50 measurements, but the coefficients of variation, $c_v = \frac{\sigma}{\mu}$, are considerable; most of them between 30% and 40%, but one as high as 53.7%. For the sake of readability of the plot, the error bars are not included in the plot.

The large variation in the measurements can have multiple causes, the first one being the fact that the grease layer is not completely evenly spread out on the capacitor. Secondly, the Elcometer has a small tip that is pushed onto the soft layer, thus distorting the measurement each time a little differently, resulting in quite different results. For the measurements with the statistics, see Appendix A-1.

Looking at the plot, one notices immediately that the values measured with the Arduino are always a tad higher than the oscilloscope measurements. From measuremeatns conducted by the acoustic sensor group, it appeared that the oscilloscope can measure frequency more accurate than the Arduino. In the next plot, figure 5-7, the average difference between the oscilloscope measurements and the Arduino measurements is deducted from the Arduino data. One other note on the plots is that the thickness of the book cover film was determined to be 51.03 μm (the first entry in the table in Appendix A-1). This value was subtracted from all of the thickness measurements, so that only the thickness of the fat layer is shown in the plots (and not the book film plus the fat). Appendix A-2 contains pictures of the capacitor with grease on it.

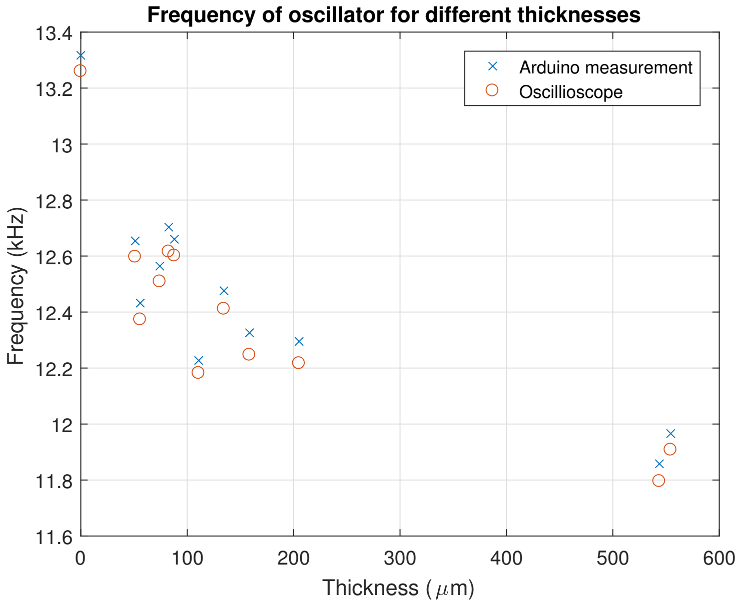


Figure 5-7: Plot of the Arduino and oscilloscope measurements.

The next step was to fit the data with a curve. The formula for the curve is:

$$f = Y0 - \left(\frac{V0}{K}\right)\left(1 - e^{-Kd}\right) \tag{5-4}$$

With $Y0 = 13.2534$, $V0 = 0.01115465$ and $K = 0.008$, d the thickness of the grease layer in μm and f the frequency in kHz. The fitted curve is shown in figure 5-8.

Now with this curve, one can determine the thickness with the frequency. Changing the formula to fit this cause yields:

$$d = -\frac{ln\left((f - Y0)\left(\frac{K}{V0}\right) + 1\right)}{K} \tag{5-5}$$

Now the system is calibrated and ready to be tested.

5-3-3 Testing the Sensor

The final step was to do new measurements, not to calibrate the system, but to test the working it. Formula 5-5 was added to the Arduino code (see Appendix A-5). This measures frequency and will also show the thickness now. There were five measurements, which are plotted in figure 5-9. The exact data can be found in Appendix A-3. The orange line is the curve y=x, because that is what you would desire; that the results measured by hand with the

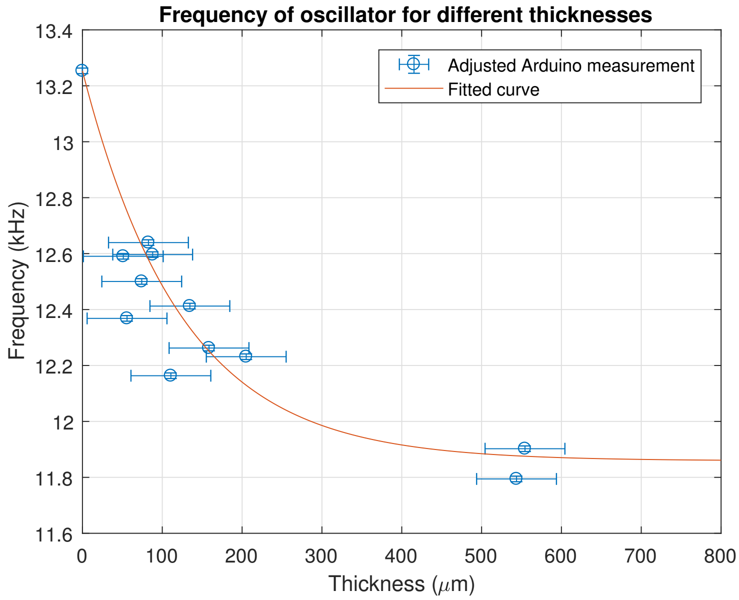


Figure 5-8: Arduino measurements corrected with the oscilloscope data and with a fitting curve.

Elcometer are the same as the Arduino measurements. These results show that the formula from fitted curve does works pretty well. The average absolute difference between the two measurements is 14.5 μm. The difference between the sensing system measurements and the ones conducted by hand ranges from 3.84 μm to 33.38 μm.

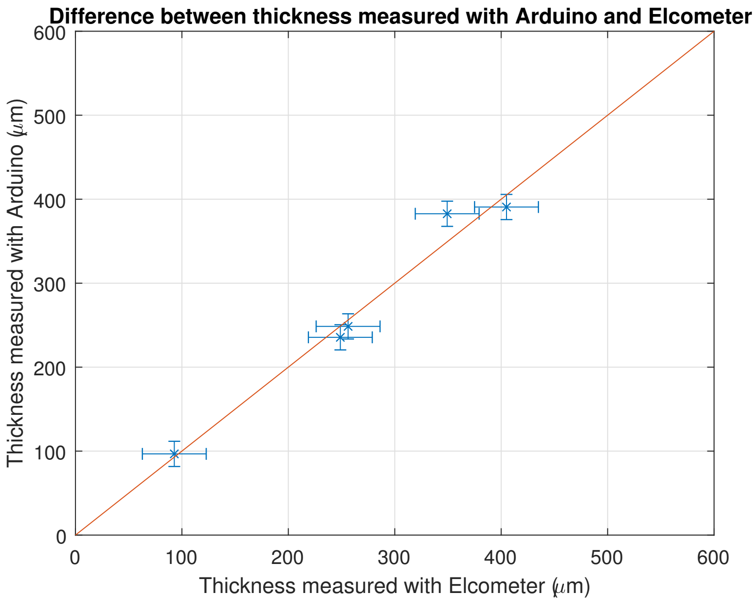


Figure 5-9: Test data show the difference between the Elcometer measurement and Arduino measurement.

Discussion

Even though the system seems to achieve reasonable results, they are, of course, not 100% accurate. This may have several reasons, as will be discussed below.

In figure 5-9 it could be seen, that the test results are not bad at all, there are only five test measurements. In order to determine if the system really works as good as it seems to do now, more measurements should be conducted. More measurements for the calibration of the system could also improve the accuracy of the system, as the curve fitting would rely on more data.

Next to this, the accuracy of measurements from the Elcometer is disputable, as the the measurement data show very high variances, as can be seen in the tables in Appendix A-1 and A-3. In figure 5-8 the data do not line up perfectly, thus leading to a fitted curve that might be fitted better, if the measurements from the Elcometer were more accurate.

Also, the Arduino does not measure the frequency as exact as one could wish. In figure 5-7 the Arduino seems to have an offset compared to the oscilloscope, but this offset is not exactly the same each time. The average difference between the two measurements was deducted from the Arduino measurements as an adjustment, but will by no means completely eliminate the problem of the Arduino measurements.

Furthermore, the calculation of the thickness does not depend on temperature so far. After the deep-frying fat was melted and poured onto the sensor, the temperature of the fat was monitored with an infrared thermometer, so that the grease would have about the same temperature during all of the measurements. Sometimes this was hard to achieve, especially the thicker layers would cool down very slowly and might be warmer under the surface than measured. A higher temperature leads to a higher capacitance (as concluded during the preliminary measurements (Chapter 4), which can be seen in figure 4-5), which leads to a lower frequency (with formula 5-1), which corresponds to a thicker layer (formula 5-5). This might explain why one of the thicker test measurements is so far off.

Because of the shape of the graph in figure 5-8, having a less steep slope for thicker layers, a small inaccuracy in the measured frequency makes for a relatively large error in the thickness, making this method more accurate for smaller thicknesses. This can also explain why the test results are better for smaller thicknesses.

Conclusion

After all the research and measurements, it is time to go back to Chapter 2 and have a look at the requirements the system was supposed to meet.

First off are the general requirements. The principles on which the system is based make sure that the orientation and the shape of the extraction channel do not affect the measurement. The sensor can be placed in any channel with any orientation.

Though the measurements are not independent of temperature, they can be adjusted for it, so that the results will be reliable for any temperature between 20°C and 100°C. The temperature sensor can work in this range and as long as the other electronics are on the outside of the duct, there will be no problem with the temperature, as the capacitor is not expected to cause any problems in this temperature range.

The consistency of the grease deposit differs per catering business, but the sensor should be able to be implemented everywhere. This system was tested with deep-frying fat, but other research conducted during the preliminary measurements showed that each type of grease will have a different impact on the capacitance. The good thing is that each type of grease is measurable, but the system has to be calibrated for each type of grease differently. The system will have to be calibrated for each type of grease. Maybe the large fast food chains could use one restaurant as an example for the others, but for small businesses it will be necessary to do some measurements in the months after placement of the system. The calibration needs to be redone after radical menu changes.

The prototype does not have its final shape yet, but the idea is to implement the sensor in the small doors in the extraction channels, so that the chemicals used during the cleaning of the extraction channels do not touch the sensing system. The only part that needs cleaning will be the surface of the interdigital capacitor, which can be easily wiped clean with a cloth.

The output that the temperature sensor and the capacitance sensor generate an be easily converted into a thickness in μm and it can measure up to 500 μm. Even though during the tests there were not thicknesses of 500 μm, the calibration in figure 5-8 shows that it should be possible to measure those thicknesses, but as mentioned in the discussion, the accuracy becomes worse. The largest error was 33 μm, but this was for about a thickness of 400 μm, so it might be higher for thicknesses of up to 600 μm, but it is hard to tell exactly, as the measurements done with the Elcometer, to which the Arduino results are compared, are not as exact themselves.

The lifetime of the sensor depends on the components that are used. No battery needs to be exchanged, as the whole circuit will be powered by the Arduino. The chemicals used during the cleaning will not wear off the sensor, because it will be cleaned by hand, so only in case of component failure will the sensor need replacement or any sort of maintenance, which is not expected to be necessary within one year after placement.

As far as known, no patents are violated. The principle of the sensor allows an infinite amount of sensors to be used in a network, so a maximum of 8 will cause no problems. The sensors do not influence each other when they are not directly next to each other. Neither will they influence the grease deposition, because the sensor will be a flat surface in the channel wall with the electronics on the outside. Only the temperature sensor might stick out a bit, but it is really small and should be placed in the design in a way that the grease deposition on the capacitor is not affected.

Future Work and Recommendations

The concept of capacitive thickness measurements has been sufficiently proven to work in the preceding chapters. The prototype did meet most of the requirements and could meet the others. In this chapter some final remarks will be made about ways to further tweak and improve the system.

First of all, the system should be tested with samples of grease from an extraction channel. During the preliminary measurements, a real sample increased the capacitance of the capacitor much more than deep-frying fat. Thinking again of the shape of the graph (figure 5-8), resulting in a lesser accuracy for higher capacitances (thicker layers), the values of the resistors in the oscillator circuit might need to be changed. The frequency of the oscillator circuit depends on the values of R and C, $f \sim \frac{1}{RC}$. So when C becomes very large, R could be adjusted.

As the crucial thicknesses to measure are the thicker ones, it is crucial that the frequency measurement is accurate, because small deviations may result in quite a different thickness. The Arduino might not be good enough to measure the frequency exact enough in the range needed. Maybe other hardware should be used in the future.

The higher permittivity of the extraction channel grease sample than the deep-frying fat might imply that it contains moist, the level of which might differ too at different locations in the system or during cooking. This could be determined with resistance measurements. This requires more research.

Though the effect of temperature was investigated, it was done so only superficially. Nonetheless it showed that temperature is absolutely a factor to be taken into account. There seems to be a linear relation between capacitance and temperature, so the adjustment for temperature should not be too hard to factor in while calculating the thickness.

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Appendix

A-1 Deep-frying Fat Frequency Measurements

Deep-frying fat frequency measurements. f_o was measured with the oscilloscope, f_a with the Arduino, the rest with the Elcometer. # is the amount of measurements with the Elcometer.

Table A-1: Deep-frying fat frequency measurements.

	Temp (°C)	f_o (kHz)	f_a (kHz)	#	Lo (μm)	Hi (μm)	$\bar{d}$ (μm)	σ (μm)	c_v (%)
#0	23.17	13.2596	13.317	11	49.6	52.9	51.03	0.98	1.9
#1	23.3	12.1817	12.2227	50	73.4	352	161.8	62	38.3
#2	23.10	12.6156	12.703	38	52.9	319	133.7	69.9	52.3
#3	22.9	12.2469	12.326	40	95.7	406	209.6	77	36.7
#4	22.85	12.2166	12.295	40	62.5	471	256.2	103.5	40.4
#5	23.41	12.5087	12.564	35	48.2	288	125.3	67.3	53.7
#6	23.41	12.4110	12.476	37	89.9	379	185.6	58	31.3
#7	23.53	11.9077	11.966	46	461	825	605.4	87.5	14.4
#8	23.76	12.5971	12.654	48	61.9	203	102.2	34.6	33.8
#9	23.87	11.7955	11.858	27	371	838	594.8	109.8	18.5
#10	23.53	12.3731	12.432	40	54.5	189	106.9	33.9	31.7
#11	23.64	12.6012	12.660	35	70.6	270	139.0	40.0	28.8

A-2 Grease on Capacitor

Figure A-1 shows the capacitor with a layer of fat. With thicker layers it is easier to make them more even.

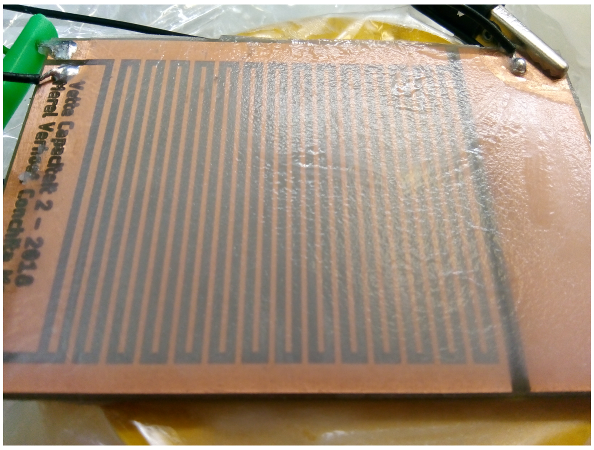

Figure A-1: Capacitor with deep-frying fat.

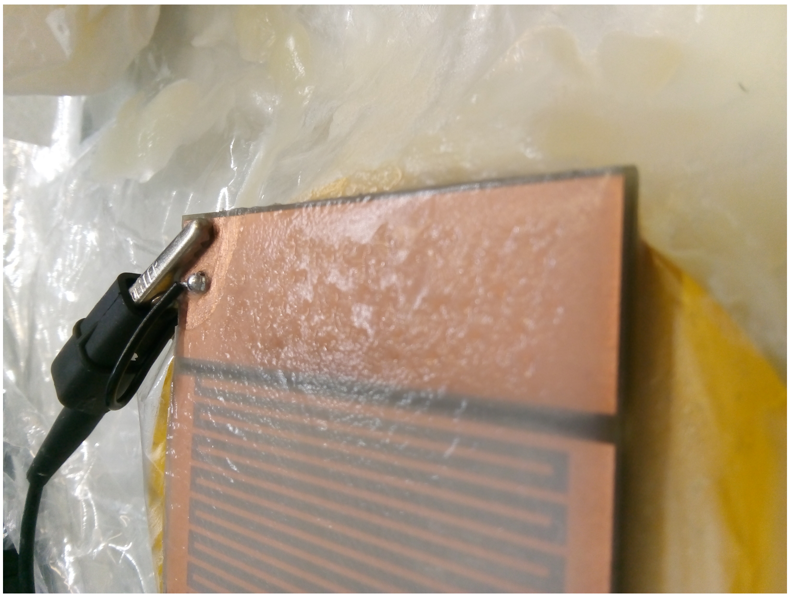

Figure A-2: The thickness measurements with the Elcometer change the surface.

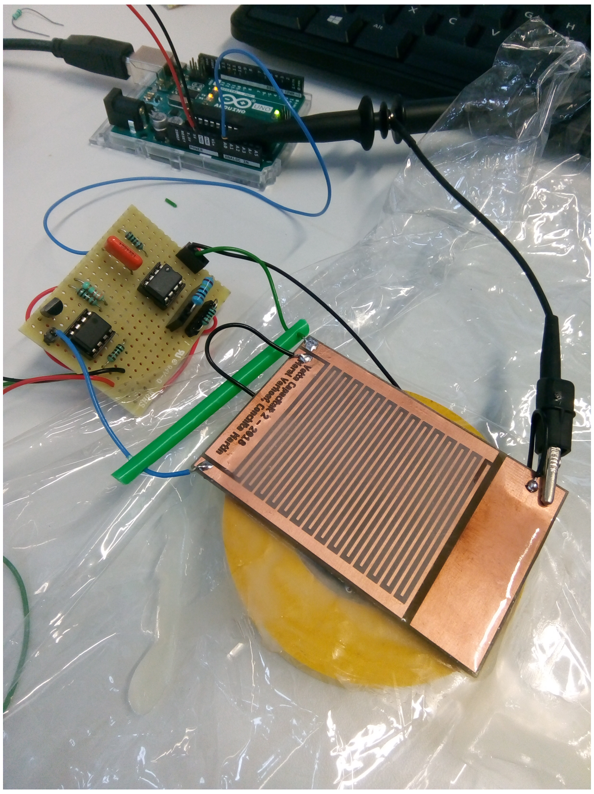

Figure A-3: Capacitor with deep-frying fat.

A-3 Test Data

Table A-2 shows the data from the test measurements. The thickness measurements from the Elcometer still include the 51.03 μm book cover foil. $\bar{d_a}$ is the thickness measured with the Arduino. f_o was measured with the oscilloscope, f_a with the Arduino.

Table A-2: Test measurement data.

	f_o (kHz)	f_a (kHz)	#	Lo (μm)	Hi (μm)	σ (μm)	c_v (%)	$\bar{d}$ (μm)	$\bar{d_a}$ (μm)
#1	12.032	12.05	51	146	559	87.4	28.4	307.2	248.53
#2	11.9060	11.92	35	207	549	91.1	22.7	400.3	382.65
#3	12.0619	12.07	28	223	473	63	21.0	299.9	235.51
#4	12.490	12.50	28	71.1	218	38.3	26.6	143.9	96.71
#5	11.9025	11.92	51	333	768	88.5	19.4	456	390.7

A-4 Arduino Code for Temperature Measurement

Listing A.1: Code for printing temperature on monitor.

```
/*
  Temperature readout

  Reads an analog input on pin 0, prints the result to the Serial Monitor.
  In this case a signal from a temperature sensor is read from input A0 ...
      and is
  converted into a temperature, which is printed on the serial monitor.
  Written by: Merel Verhoef, June 9. 2018

*/

// the setup routine runs once when you press reset:
void setup() {
  // initialize serial communication at 9600 bits per second:
  Serial.begin(9600);
}

// the loop routine runs over and over again forever:
void loop() {
  //op amp gain
  double gain = 4.3;
  //sensor 10mV/degree
  double sensor = 0.01;
  //factor to multiply input pin 0; 5V in 1023 steps
  double factor = 5/(sensor*1023*gain);
  // read the input on analog pin 0:
  double sensorValue = analogRead(A0);
  // calculate temperature:
  double temperature = factor*sensorValue;
  // print out the temperature:
  Serial.println(temperature);
  delay(1);        // delay in between reads for stability
```

```
}
```

A-5 Arduino Code for Frequency Measurement and Thickness Calculation

Listing A.2: Code for frequency measurement and thickness calculation.

```
// defines for setting and clearing register bits
#ifndef cbi
#define cbi(sfr, bit) (_SFR_BYTE(sfr) &= ¬_BV(bit))
#endif
#ifndef sbi
#define sbi(sfr, bit) (_SFR_BYTE(sfr) |= _BV(bit))
#endif



void setup() {
  Serial.begin(9600);
  cbi(ADCSRA,ADPS2) ;
  sbi(ADCSRA,ADPS1) ;
  cbi(ADCSRA,ADPS0) ;
  for(int i = 2; i < 11; i++) pinMode(i, OUTPUT);
}

void loop() {
  double freq = makeFreqMeting(3000);
  double y0 =13.2534;
  double v0 = 0.01115465;
  double k = 0.008;
  double off = 0.0636; //offset compared to oscillator
  double freqk = (freq*0.001)-off;
  double thickness = -(log(((freqk-y0)*(k/v0))+1)/k);


  Serial.println(freqk);
  Serial.println(thickness);


}



double makeFreqMeting(int times){

  double totfreq = 0;
  int timesrun = 0;

  while(timesrun<times){
  int lengthofr = 300; //amount of samples taken
  unsigned short recvalues[lengthofr]; //array with sample values
  int time1 = 0;
  int time2 = 0;
```

```
  int i = 0;

  int high = 0;
  int pers = 0;

  double tottime=0;
  double freq=0;

  time1 = micros(); //time in microseconds
  for(i = 0; i < lengthofr; i++){
    recvalues[i] = analogRead(0);
  }
  time2 = micros(); //time in microseconds

  for(i = 0; i < lengthofr; i++){
     if(recvalues[i]>800 && high==0){
      pers++;
      high=1;
     }
     if(recvalues[i]<200 && high==1){
      pers++;
      high=0;
     }
  }
  tottime = (time2-time1) * 0.000001;
  freq = ((double)pers)/(2*tottime);
  totfreq = (totfreq*timesrun+freq)/(timesrun+1);
  timesrun++;
  }
  return totfreq;
}
```