Universidade de Aveiro
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João André de Jesus Cruz

Telemetria para Vasilhame baseada em IoT

IoT-based Telemetry for Containers

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Dissertação apresentada à Universidade de Aveiro para cumprimento dos requesitos necessários à obtenção de grau de Mestre em Engenharia Eletrónica e Telecomunicações, realizada sob a orientação científica do Professor Doutor Pedro Nicolau Faria da Fonseca, Professor Auxiliar e coorientação do Professor Doutor Paulo Bacelar Reis Pedreiras, Professor Auxiliar do Departamento de Eletrónica, Telecomunicações e Informática da Universidade de Aveiro

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Palavras-Chave Gases de petróleo liquefeito, FFT, Acelerómetro, Piezoeléctrico

Resumo

Esta dissertação apresenta um estudo efectuado com o intuito de desenvolver um dispositivo capaz de medir a quantidade de gás líquido dentro de uma garrafa, de forma não evasiva. A investigação realizada resultou na identificação de diferentes métodos de medição de nível, como por exemplo a medição do peso, a análise das vibrações resultantes da estimulação externa, entre outros. Da investigação para a escolha do método de identificação de nível de líquido, optou-se por desenvolver o trabalho com base na análise das vibrações produzidas quando estimulada a garrafa.

O trabalho dividiu-se em diferentes objetivos, todos com vista ao desenvolvimento de um dispositivo que se enquadre no propósito. Inicialmente, recorreu-se a um microfone com o intuito de captar a resposta da garrafa a um estimulo externo. Realizou-se a análise do sinal captado no domínio da frequência, com base na implementação e validação da FFT num microcontrolador de baixo consumo. Posteriormente, realizou-se um estudo e análise de vários sensores nomeadamente,um acelerómetro e um piezoelétrico, de modo a substituir o microfone previamente selecionado. Por fim procedeu-se ao desenvolvimento de um algoritmo de identificação de nível, com base nas vibrações captadas pelos sensores, que permita distinguir as diferentes garrafas utilizadas em testes.

Keywords Liquefied petroleum gas, FFT, Accelerometer, Piezoelectric

Abstract This dissertation presentes the study made with the intent of developing a device capable of measuring the amount of liquid gas inside a bottle, in a non evasive way. The realized investigation resulted in the identification of diferent methods to measure the level, as for example the weight measure, the vibrations analisys from the external stimulation, among others. From the investigation to select the liquid level identification, it was chosen to develop the work based on the analisys of the vibrations produced when stimulated.

The work was divided with different objectives, all of them with the development of a device that fits in the purpose in perspective. Initially, a microphone was used in order to capture the bottle's response to an external stimulus. An analysis of the signal captured in the frequency domain was carried out, based on the implementation and validation of the FFT in a low-power microcontroller. Subsequently, a study and analysis of several sensors was accomplished, namely, an accelerometer and a piezoelectric, in order to replace the previously selected microphone.Finally, was developed an algorithm to the level identification, based on the vibrations captured with the sensors, that allow to distinguish between the three bottles used in the tests.

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Acronyms

AD Analog

ADC Analog to Digital Converter

BCRM Branded Cylinder Recirculation Model

bps bits per second

CCCM Consumer Controlled Cylinder Model

CPU Central Process Unit

DFT Discrete Fourier-Transform

DMA Direct Memory Access

DTFT Discrete-Time Fourier-Transform

eUSCI Enhanced Universal Serial Communication Interface

FFT Fast Fourier Transform

FRAM ferroelectric RAM

I^2C Inter-Integrated Circuit

iFFT inverse Fast Fourier-Transform

IoT Internet of Things

IrDA Infrared Data Association

LDV Laser-Doppler Vibrometer

LPG Liquefied Petroleum Gas

LSB least lignificant bit

LTI Linear Time-Invariance

LVDT Linear Variable Differential Transmitter

MATLAB MATrix LABoratory

MEMS Micro Electro Mechanical Systems

MOSFET Metal Oxide Semiconductor Field Effect Transistor

OpAmp Operational Amplifier

PC Personal Computer

PCB Printed Circuit Board

PVDF Polyvinylidene Fluoride

PZT Lead zirconate titanate

RAM Random Access Memory

RISC Reduced Instruction Set Computer

RTC real-time clock

SNR Signal-to-noise Ratio

SPI Serial Peripheral Interface

TI Texas Instruments

UART Universal Asynchronous Receiver-Transmitter

USB Universal Serial Bus

Wi-Fi Wireless Fidelity

Chapter 1

Introduction

1.1 Background and Motivation

Energy plays an important role in our modern lifestyle and the development process of any country. Studies shown a strong correlation between the energy production/consumption and the economic/scientific development. Back in a couple of centuries ago, the primary source of energy was wood. As the industrialization evolution began, the need for energy sources with higher rates of energy efficiency emerged[1]. The first successor was charcoal followed, a few years latter by oil and LPG(Liquefied Petroleum Gas). Compared with the other energy sources, LPG burns very efficiently, emitting smaller amounts of pollutants gases. For example, to produce the same amount of energy produced by 1Kg of LPG, burning it in a cookstove, it would be needed approximately at least 2.5Kg of charcoal and 21Kg of raw wood [2].

LPG is the second biggest, non-renewable, source of energy in the world, with different consumption areas, as domestic, auto, industrial and agriculture. It has a highest consume in a domestic level, since is used to heating and cooking. The various types of LPG are produced by the extraction of natural gas, oil extraction and oil refining. Propane, butane and natural gas are the most common types of LPG, used in house appliances [3]. More recently the energy sources have been replaced with renewable energy, to decrease the global warming and despite LPG huge impact, does not seem that it would not be replaced by other sources of energy, since recent studies developed what can be considered a renewable method of biosynthesis propane gas [4], commonly used in house appliances.

The LPG use in house appliances, usually is made via pluming systems in the cities, where the agglomeration of population is higher, which turns the pipelines gas installations more economic viable when compared with other regions. For smaller villages the solution for the LPG distribution is based on the gas cylinders, which is divided in two main distribution systems, Consumer Controlled Cylinder Model, where the final consumer is responsible for refueling the cylinder, most commonly used in cars, and Branded Cylinder Recirculation Model, where the final consumer only exchange a empty cylinder for a full one, being the supplier responsible for its refill, which require additional logistics for the suppliers distributions systems. For the second, it would be interesting for the suppliers and the cylinder retailers, to know the amount of gas in the cylinder of each final consumer of a certain region of supply.

This motivated a research in a accurate method of measuring the amount of gas in a LPG cylinder and the information transmission to the supplier, taking advantage of the technology and using a IoT, as a way to transfer the information, suppliers would be able to efficiently plan their distribution routes.

In a initial stage it will be explored different methods of measuring the level of gas in a LPG cylinder and the the work developed is based in one of those methods. All the details will be explained along the document.

1.2 Scope

This work explores the possibility of develop a device capable of measuring the liquid gas inside a bottle in a non invasive way.

Initially will be made a study of devices with similar purpose, this will allow the proposal of an architecture to a system capable of measure, process and identify the liquid gas inside the cylinder. This must be followed by the implementation of the proposed solution. In the end it will be performed individual tests to each piece of the system, concluding with the identification test.

1.3 Outline

This dissertation is divided in seven different chapters. The first chapter gives a general overview of the motivation behind the dissertation and defines the objectives to archive in the development of the work.

The second starts by some background information, about previous works with similar purpose and a brief explanation of the theoretical components behind the work to develop. This chapter is the basis to define a solution to approach the problem presented.

The third is where is defined the approach to solve the presented work, it is presented all the necessary elements of the system to developed a general system architecture suggested.

The elements are defined in fourth and fifth chapters. The first relative to the physical, or hardware, elements that will be part of the system and the second is defined concerns about the software and the details of the integration of the hardware with the software.

The sixth chapter, is dedicated to present the different tests, their results and their analysis. The tests performed will serve as a basis to the continuation and integration of all parts in to what was proposed in chapter three.

The work is finishes with Chapter seven, where are made some final considerations about the developed work, as well as suggestions for the future work.

Chapter 2

State of the Art

This chapter will present several topics related to the LPG cylinder, previous works, systems concepts important for the work. To understand how to properly measure the liquid level, is important to know how the cylinder is constituted and what can indicate the variation of the liquid level. After it, is important to make a background search in previous works and their approaches, to understand if it is feasible and what is the approach to be taken. When selecting the technique to use for the purpose of the solution and before getting into the theoretical details of it, is necessary to understand what is related to the system, in a engineering point of view. In the end, is presented different sensors, that can be used according to the type of measurements pretended in future product.

2.1 The LPG cylinder

The LPG cylinders commonly used in house appliances, usually come in different weight types, that change according to the cylinder construction, supplier, application and composition of gas that is being held inside the container. One thing that is similar is the state of the gas under certain circumstances, for instance the boiling point of LPG is around -42ºC, this means that is in a gaseous state at ambient temperature/pressure.

Usually when the LPG cylinder is full, the gas is kept in a liquid and gas form, in a percentage of around 80% and 20%, respectively, with a constant pressure, this percentage allows, when the external temperature rises, affecting the internal temperature, for both gas and liquid to expand until a certain limit, without compromise the safety of the use of the cylinders.

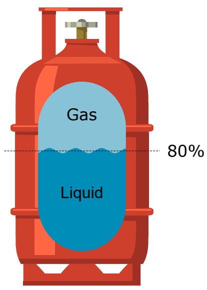


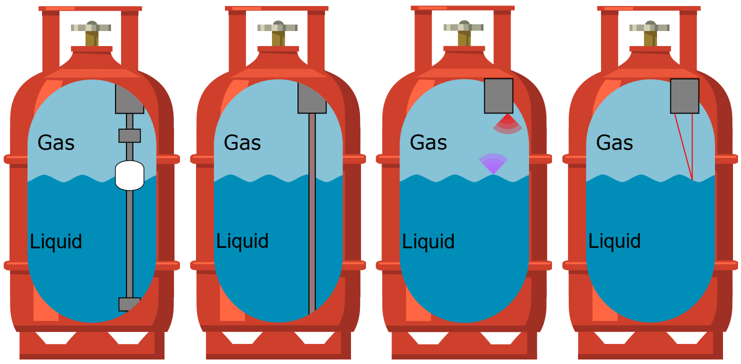
Figure 2.1: LPG cylinder internal state composition

When the cylinders are empty and need to be filled, there is a direct relation between the amount of pressure, needed to fill the cylinders, and the temperature of the gas, the higher the temperature of the gas the higher is the pressure needed to fill the cylinder, this process of turning the LPG in a gas form into a liquid by pressurizing it, is called liquefaction. Other relation that should be considered is related with the weight of the cylinder and the amount of liquid gas inside. When the valve is open, gas is released and the liquid turns into gas, to keep the pressure balance inside. Since the density of the liquid is higher than the gas and when the valve is open, the liquid turns into gas, the liquid decreases so the weight of the cylinder [5, 6].

2.2 Measuring/Stimulation Techniques

2.2.1 Measuring Techniques

As the LPG cylinder is divided in two physical states, liquid and gaseous, the liquid gas what defines the amount of gas inside. Several techniques have been used to determine the liquid level, being some of those based in the same methods. Those methods are usually split in two different categories, contact and contactless. Contact measuring methods usually include mechanical, electrical or pressure sensing devices. In these methods the sensors are in direct contact with the liquid. In contactless, the methods used usually are more complex to process, when compared with contact methods. In this case the methods of measuring are mainly through optical, ultra-sound, vibration and weight analysis [7].



(a) (b) (c) (d)

Figure 2.2: Different LPG cylinder to used to compare the relation between Frequency and Weight for different models

[8]

Considering the fact that the LPG cylinder is opaque and isolated, some of methods can not be used in the process. For instance mechanical float-type or an electrode are not suitable for the application, since it would require their installation during the fabrication of the cylinder, implying the substitution of the current cylinders. In the same way, in contactless methods, the use of different optical techniques and the use of ultra-sound, would face the same problem mentioned with the contact methods, since some of them would require the installation during the fabrication process, being also discard as a suitable method in this situation.

From previous research, some work has already been developed with the purpose of measuring the amount of liquid gas inside a LPG cylinder. In a work from Baig and Elahi[9] a pressure sensing device was developed, with the final appliance to a LPG cars, but with the possibility of apply in other circumstances. The device uses the pressure variation to move a magnet and using a Hall Effect sensor, with a fixed position, this motion produces a linear change of the voltage in the sensor, giving an accurate method of measuring the amount of gas in the LPG cylinder, in this case.

A common method of evaluate the amount of gas inside a LPG cylinder, is based on the weight change of the cylinder, that decreases with the consumption of liquid gas. As an example, the work developed by da Silva Medeiros et al., Shrestha, Anne, and Chaitanya or Shingan et al. have similar approaches to measure the amount of liquid gas inside the LPG cylinder. There are various works based on this technique since is very simple to implement and very precise, it only requires a load cell, an amplifier, a microcontroller and a method to display the results, and unless there is a huge change in the external temperature, the density of the gas will not be much affected and thus not affecting the weight of the bottle [10, 11, 12]. Another method, that proved to be valid for measuring the amount of liquid inside a closed opaque container, is based on the analysis of the resulting vibrations when the container is stimulated by a external source. Depending in the type of the stimulation, it can produce only vibration, or it can also produce a characteristic sound, for different levels. As an example of two approaches based on the same principle are the works from Jahn, Ehrle, and Roppel and Wu et al., in both cases the vibrations are analyzed, in one case is the vibration of the tank and in the other is through the sound produced by the tank vibration [13, 14].

2.2.2 Stimulation Techniques

Taking into consideration, that the measurement of the liquid level is based on vibration, one of the methods to induce vibration is based on a piezoelectric transducer, attached to the bottom of the container. This transducer produces transversal and longitudinal waves in the surface of the container, where the transducer is attached. The frequency of the waves generated is related with the frequency of the system response to a certain liquid level, and changes according to that. The same waves are captured with another piezoelectric transducer and processed [13].

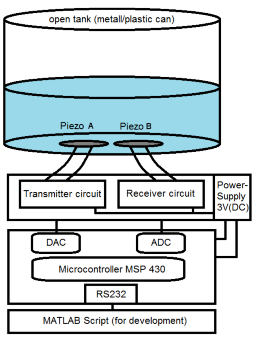


Figure 2.3: Stimulation and measuring system based on piezo transducer
[13]

Another method to produce vibration in the LPG bottle, can be achieved with a hammer or a device that hits the surface of the LPG bottle. The captured signal is then processed and the result returns the level of liquid gas inside [14].

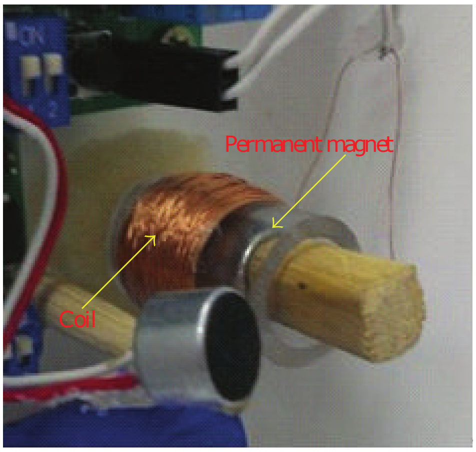


Figure 2.4: Stimulation system based on a knocking device
[14]

2.3 Signals and System

2.3.1 Vibration

The vibration and the studies in this field are usually related with the oscillatory motion of a body and the forces associated with them. Bodies with mass and elasticity are capable of experience vibration, knowing that, for example, when a structure is designed, the oscillatory behavior of the structure must be considered. There are two types of vibration, free and forced. The first takes place when a system oscillates under forces natural to the system itself and there is no action of external forces. Under free vibration the system will vibrate at one or more of its natural frequencies, stablished by the properties of the system. Forced vibration occurs when the system is under the excitation of external forces. The system will vibrate at the same frequency of the external oscillation, if this frequency matches one of its natural frequencies a resonant state is reached.

2.3.2 Signal definition

Signals can describe a large variety of physical phenomenon, bringing a certain information about it, depending of the phenomenon represented. For example, the voltage variation in a capacitor, or the human voice which creates variations in acoustic pressure, captured by a microphone that senses those variations and convert them into a electrical signal. A signal can be represented mathematically as a function of one or more independent variables.

To what concern in signal processing, the types of signal considered are two, continuous-time signals and discrete-time signals. In these cases the independent variable, the time, is continuous and discrete, respectively [15].

2.3.3 Signal and Digitalization

A continuous-time signal can be represented in a discrete-time form by the knowledge of its values at certain points in time equally spaced. This is called sampling, and if the samples are close to each other, less time between samples, the more similar the discrete signal became to the continuous. Sampling plays an important role between the continuous-time and the discrete-time.

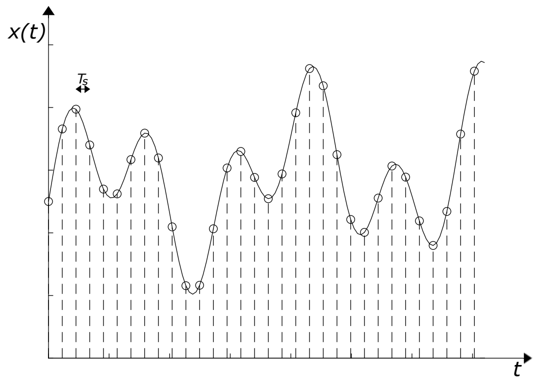


Figure 2.5: Signal sampling

Considering a continuous-time signal $x(t)$ is measured at every T_s seconds. The is discretized in units of the sampling interval T_s:

$$t = nT_s,\ n = 0, 1, 2, ...$$

The variable T_s is called sampling period and the inverse of the period $f_s = \frac{1}{T_s}$ is the sampling frequency. One of the problems of this conversion is usually related with the correct choose of the sampling period, that must be small enough so if there are small variations in the signal, they do not get lost between samples. Therefore the the sampling frequency f_s must be chosen to be greater than twice the maximum frequency f_{max} measured. A continuous-time signal $x(t)$ is bandlimited, so its frequency spectrum is limited at maximum frequency f_{max}, and no frequencies above that.

$$f_s > 2f_{max} \tag{2.1}$$

$$T_s < \frac{1}{2f_{max}} \tag{2.2}$$

The minimum value of the sampling frequency allowed by the theorem, is called the Nyquist rate, and his value is $f_s > 2f_{max}$. Oppositely, for a known value of f_s the maximum frequency of the signal is $f_{max} < \frac{f_s}{2}$.

For the representation of some signals is usually used a unit impulse as a method to build a block to represent and construct other signals. The definition of a unit impulse (or unit sample), in discrete-time, is defined as follows:

$$\delta(n) = \begin{cases} 0, n \neq 0 \\ 1, n = 0 \end{cases} \tag{2.3}$$

Another example of a simple discrete-time signal is the unit step, defined as:

$$u(n) = \begin{cases} 0, n < 0 \\ 1, n \geq 0 \end{cases} \tag{2.4}$$

If a close analysis is made, is possible to conclude that there is a relation between a unit impulse and a unit step, a unit step can be represented as a sum of impulses

$$u(n) = \sum_{k=0}^{\infty} \delta(n-k) \tag{2.5}$$

The equation 2.5 can be seen as a sum of delayed impulses and plays an important role in the sampling property.

The values of the f_{max} and f_s depend on the application, and the Nyquist frequency usually defines the cutoff frequencies used in filters required in DSP applications. A example of the of the typical sampling rates of common DSP applications are shown in table 2.1.

application	f_max	f_s
geophysical	500 Hz	1 kHz
biomedical	1 kHz	2 kHz
mechanical	2 kHz	4 kHz
speech	4 kHz	8 kHz
audio	20 kHz	40 kHz
video	4 MHz	8MHz

Table 2.1: Common sampling rates per application
[16]

2.3.4 System definition

There is no specific nature to a system, and there is vast example of systems all around us, they could be biological, mechanical, electrical, among others. In the signal processing context a system can be viewed as a process in which input signals are transformed by the system or cause the system to respond in some way, with the resulting in new output signals. Simplifying, a system can be described as an entity with a specific function, where the output signal is the result of the manipulation one or more input signals.

The types of signals mentioned, continuous and discrete, the systems usually are represented as in the equation 2.6, in both cases x represents input and y output.

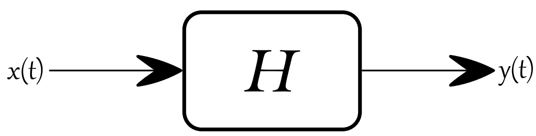


Figure 2.6: Generic system

$$y(t) = H[x(t)]$$
$$y(n) = H[x(n)] \tag{2.6}$$

One of the motivations for the study/analysis of systems from various applications, thus systems from different applications, with similar behavior, can have similar mathematical descriptions. The description of a system as a mathematical function also allows to simulate the behavior in a certain application, testing the response of it with different techniques.

A system can be described with certain properties, each one having a different effect on the system output. The properties are stability, memory, causality, invertibility, time-invariance and linearity. In signal-processing context, invertibility and time-invariance have special relevance, with a profound study of linear time-invariant(LTI) systems further ahead [15, 17].

Stability

A system is considered stable if an input signal limited in amplitude, results in a output signal also limited in amplitude. The system operation, H, is stable if the output signal $y(t)$ satisfies the following condition

$$|y(t)| \leq M_y < \infty, \forall t \tag{2.7}$$

If the input signal $x(t)$ satisfies the condition

$$|x(t)| \leq M_x < \infty, \forall t \tag{2.8}$$

The values of M_x and M_y correspond to finite positive numbers. The conditions for the stability of a discrete-time system can be described in the same way.

Memory

A system has memory, when the output signal depends on past values of the input signal. The temporal extension of the past values on which the output depends, defines how far the memory of the system extends. One example of a system with memory is the current $i(t)$ in a inductor and the relation of his voltage $v(t)$:

$$i(t) = \frac{1}{L}\int_{-\infty} tv(\tau)d\tau \tag{2.9}$$

For a discrete-time system, the conditions are similar.

Causality

A system is considered *causal* if his resulting output signal, only depends in present/past values of the input signal. Opposed to that, a *noncausal* system can have is output depending on future values of the input signal. An example of a *causal* output is the following:

$$y(n) = \frac{1}{3}(x(n) + x(n-1) + x(n-2)) \tag{2.10}$$

On the other hand an example of a *noncausal* is:

$$y(n) = \frac{1}{3}(x(n+1) + x(n) + x(n-1)) \tag{2.11}$$

For a continuous-time system, the conditions are similar.

Invertibility

A system is considered invertible if is possible to recover the input from the output signal of the system. The operation to recover the signal may be a different system connected to the output of the first. If the operation of a system is represented with H in a continuous-time domain, with $x(t)$ and $y(t)$ being the input and output, respectively. The $y(t)$ is applied to the second system, where the result is expected to be $x(t)$, as follows:

$$\begin{aligned} H^{-1}y(t) &= H^{-1}H\{x(t)\} \\ &= H^{-1}H\{x(t)\} \end{aligned} \tag{2.12}$$

As the $H^{-1}H$ denotes the identity operation. If H^{-1} is the inverse operation of the H then the output of the second operation is the same as the input of the first operation. For a discrete-time system, the conditions are similar.

Time-Invariance

A system is considered time invariant if a time delay in the input signal, results in a delay of the same magnitude of the output signal. This means that a certain system will respond in the same way, whenever a signal is applied in input, meaning that the characteristics of the system will not change with time. Considering a continuous-time system, with $x(t)$ and $y(t)$ being the input and the output, respectively. Represented as follows:

$$y(t) = H\{x(t)\} \tag{2.13}$$

If the input signal is delayed by t_0 seconds, the new input signal is $x(t-t_0)$ and an be described as follows:

$$x(t-t_0) = S^{t_0}\{x(t)\} \tag{2.14}$$

Where the S^{t_0} represents the delay. So the new output signal $y_i(t)$, resulting from the delay applied in the will be:

$$\begin{aligned} y_i(t) &= H\{x(t-t_0)\} \\ &= H\{S^{t_0}\{x(t)\}\} \\ &= HS^{t_0}\{x(t)\} \end{aligned} \tag{2.15}$$

Now considering y_o the output signal of the original system delayed by t_0 seconds:

$$\begin{aligned} y_i(t) &= S^{t_0}\{y(t)\} \\ &= S^{t_0}\{H\{x(t)\}\} \\ &= S^{t_0}H\{x(t)\} \end{aligned} \tag{2.16}$$

The system is time invariant if the outputs are equal for an identical input signal $x(t)$.

$$HS^{t_0} = S^{t_0}H \tag{2.17}$$

This means that, for a system H to be time invariant, the system H and the time delay S^{t_0} must commute with each other for t_0. A similar relation in the discrete-time system to be time invariant. For a discrete-time system, the conditions are similar.

Linearity

A system is considered *linear* if fills all the requirements of the *principle of superposition*. That is, if the response of a system to a weighted sum of input signals is equal to the same weighted sum of the output signals, in each one of the output signals being the result of a certain input signal acting independently in the system. If this principle is not fulfilled, the system is called *nonlinear*. A weighted sum of continuous-time signals:

$$x(t) = \sum_{i=1}^{N} a_i x_i(t) \tag{2.18}$$

Is applied to a system H, where $a_1, a_2, ..., a_N$ correspond the weight factor and $x_1(t), x_2(t), ..., x_N(t)$ correspond to the input signals. Resulting in the system response as represented:

$$\begin{aligned} y(t) &= H\{x(t)\} \\ &= H\left\{\sum_{i=1}^{N} a_i x_i(t)\right\} \end{aligned} \tag{2.19}$$

If the system is linear, then the weighted sum of output signals is:

$$\begin{aligned} y(t) &= \sum_{i=1}^{N} a_i y_i(t) \\ y_i(t) &= H\{x_i(t)\} \end{aligned} \tag{2.20}$$

This result in

$$y(t) = \sum_{i=1}^{N} a_i H\{x_i(t)\} \tag{2.21}$$

which is the equivalent mathematical representation as in a weighted sum of inputs. To represent them in the same form, the system operation can commute with the amplitude and sum scaling. This principle also applies to discrete-time systems in a similar form.

2.3.5 LTI Systems

As systems can be found all around us, so does a LPG bottle can be considered as a system. If the mathematical model that represents it meet the last two properties mentioned, Time-Invariance and Linearity, it can be referred as a Linear Time-Invariance system. These properties combined with the characteristics of the unit impulse, are able to represent common signals as a representation of combined delayed impulses, this allows to completely characterize a LTI from his impulse response [15, 17]. Similar to a unit step $u(n)$, a common signal $x(n)$ can be represented by unit impulses, as follows:

$$x(n) = \sum_{k=-\infty}^{+\infty} x(k)\delta(n-k) \tag{2.22}$$

In this case the weights in the linear combination are $x(k)$. Another aspect to take in consideration in these types of systems, is the response of the system to a impulse $\delta(n)$, results in

$h(n) = H[\delta(n)]$. With this in mind, the response of a linear system $y(n)$ to a common input signal $x(n)$, represented from a combination of shifted impulse, can be represented as:

$$\begin{aligned} y(n) &= H\big[x(n)\big] \\ &= \textstyle\sum_{k=-\infty}^{+\infty} x(k)h(n-k) \end{aligned} \tag{2.23}$$

The result is known as the *convolution sum* or *superposition sum* and the operation as *convolution* of the sequences $x(n)$ and $h(n)$. The operation can be represented as:

$$y(n) = x(n) * h(n) \tag{2.24}$$

2.3.6 Discrete-Time Fourier-Transform

For the analysis of LTI systems, one of the most powerful and used tools is the Fourier-Series and Fourier Transform. For the analysis purpose, the focus is only going to be the Discrete-Time Fourier-Transform (DTFT). The study of this type of systems offers two great advantages:

- It is possible to construct an extensive and convenient class of signals, based on a set of simpler signals.
- The response of the LTI signal should be simple enough, to provide a convenient representation of the response from the system to any signal based on the combination of several other basic signals.

The properties are provided by a set of exponential signals, this is important because the response of a LTI system to a complex exponential input is the same exponential with the change in amplitude.

For the analysis purpose, is necessary to know the representation of a signal $x(n)$, that later is going to be represented as an input of a system. The signal is represented in the frequency domain, where ω represents the *angular frequency*, and its period is 2π. The signal is represented as follows:

$$X(e^{\jmath\omega}) = \sum_{n=-\infty}^{+\infty} x(n)e^{-\jmath\omega n} \tag{2.25}$$

As mentioned in 2.3.5, the response of a LTI system to a impulse, can be represented by the *convolution* operation. This operation can be represented in the frequency domain as:

$$Y(e^{\jmath\omega}) = X(e^{\jmath\omega})H(e^{\jmath\omega}) \tag{2.26}$$

Where the terms $X(e^{\jmath\omega})$, $H(e^{\jmath\omega})$ and $Y(e^{\jmath\omega})$ are the Fourier transforms of $x(n)$, $h(n)$ and $y(n)$, respectively. The *convolution* operation in the LTI system, is easily represented using the Fourier transform with a simple algebraic operation, by multiplying the Fourier transforms. This facilitates the analysis of the signals and systems and increases the understanding in the behavior of the LTI system when a signal is applied to its input.

With this work in consideration, a algorithm was presented by Cooley and Tukey, the fast Fourier Transform, or simply FFT. This algorithm later proved to be suitable for a digital implementation, with its reducing time in computing the transforms by order of magnitude [15].

2.4 LPG cylinder Model

As already mentioned in 2.3.4, is possible to describe an LPG cylinder through a mathematical function, as a system. In many cases their mathematical representation is similar to other systems. The fact that the system is described as a mathematical model allows to understand what it could be the behavior of it.

The work developed by Wu and Yang[8] proposes a model for the LPG cylinder, based on vibrations to perform measurements.

Their procedure was simple, when knocking the surface of the cylinder, this produces a sound. The sound generated changed with the liquid level inside. Considering this, they have measured and processed the sound produced. From their analysis of the results they have found a relation between the frequency of the sound and the liquid level.

Before them, other researchers studied the transverse vibration of cylindrical tubes with variable levels of liquid inside. One of them is the work of Chan and Zhang[18], who proposed a vibration model (clamped-free model), where a tube clamped at bottom and free at top, was used to study the relations resonant frequencies versus liquid levels. Their tests were conducted under a controlled environment, for different levels of liquid, and the experimental results obtained were in accordance with the theoretical calculations [18].

Their work was then extended with a different approach by Chan, Leung, and Wong, the model they proposed study the vibration of a simply supported beam with uniform mass, partially loaded, in one of the sides, with a distributed mass(pinned-pinned model). For the conducted tests, the load length increased until reaching the length of the beam, the results obtained in their measurements agreed with the results obtained from the previous work [19].

A few years later Jacobs et al. proposed a similar model to Chan and Zhang model, but this time with different boundaries, clamped at bottom and top (clamped-clamped model). The tests conducted measure the resonant frequency of the tube, for different levels of liquid, their results fitted with the results obtained in the previous mentioned tests [20].

Like in the previous studies, the base of the work developed by Wu and Yang is the Euler-Bernoulli beam theory [21, 22], this is used to create a model of a cylindrical tube, allowing to estimate the vibration frequency, for different liquid levels. In their work they were able to prove that this theory can be applied to the vibrations in a LPG cylinder, where the results obtain were similar to the results obtained in previous works, based in the same principal.

2.4.1 Mathematical Model for LPG cylinder

The similarities with the Euler-Bernoulli theory and its models, with a LPG cylinder, is related with the construction of the cylinder. A common LPG cylinder used in house appliances has two welded seams, located at the bottom and the top, and those seams are considered the boundaries of the LPG. These boundaries are not considered to be free, but loose instead, which does not allow to immediately identify the the type of boundaries of the cylinder. Before getting into a conclusion is necessary to understand the theory behind their work.

If a hammer is used to knock the surface of the LPG cylinder, this will trigger a transverse vibration, considered in this case a mechanical vibration. The resulting change in the frequency vibration, according to the liquid level, is similar to what was observed in the Euler-Bernoulli beam theory, assuming a distributed mass per unit of length m, partially loaded with a distributed mass as well m_d, corresponds in this situation to the liquid part of the cylinder. In figure 2.7 is identified the boundaries and is illustrated the LPG cylinder model, the equation 2.27 describe the vibratory model of the LPG cylinder. The liquid-gas interface corresponds to the origin, and EI is a constant value corresponding to the the beam flexural rigidity.

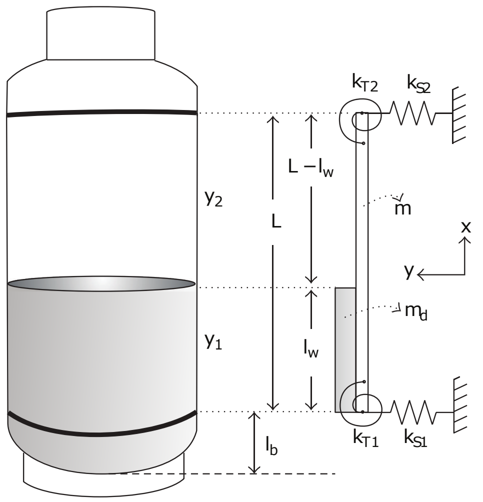


Figure 2.7: The LPG cylinder filled with liquid, with the mechanical representation of the Euler-Bernoulli beam

[8]

$$
\begin{aligned}
EI\frac{\partial^4 y_1}{\partial x^4} + (m+m_d)\frac{\partial^2 y_1}{\partial t^2} &= 0, \text{ for } -l_w \le x < 0 \\
EI\frac{\partial^4 y_2}{\partial x^4} + m\frac{\partial^2 y_2}{\partial t^2} &= 0, \text{ for } 0 < x < L - l_w
\end{aligned}
\tag{2.27}
$$

The variables y_1 and y_2 correspond to the transverse vibratory displacements of the beam, with y_1 referring to the liquid state and y_2 to the gaseous state. Considering that the seam welding's are not ideally clamped or pinned, and the main transverse vibration is restricted between the two boundaries, is assumed that they have small displacements, that will show flexural vibration. This way their model assumes that there is strong linear springs and torsional springs connected at the boundaries. Which obligates to the boundaries conditions to be formulated taking in consideration these factors, where k_{S1}, k_{T1} are the linear and torsional springs constants for the lower welding, and k_{S2}, k_{T2} are the correspondent spring constants in the upper welding.

$$
\begin{aligned}
At\ x = -l_w &\Rightarrow \begin{cases} EI\frac{\partial^2 y_1}{\partial x^2} = -k_{T1}\frac{\partial y_1(-l_w,t)}{\partial x} \\ EI\frac{\partial^3 y_1(-l_w,t)}{\partial x^3} = -k_{S1}.y_1 \end{cases} \\
At\ x = L - l_w &\Rightarrow \begin{cases} EI\frac{\partial^2 y_2}{\partial x^2} = -k_{T2}\frac{\partial y_2(L-l_w,t)}{\partial x} \\ EI\frac{\partial^3 y_2(L-l_w,t)}{\partial x^3} = -k_{S2}.y_2 \end{cases}
\end{aligned}
\tag{2.28}
$$

At the bottom a circular steel plate is attached to make the cylinder more stable in relation with the ground, this turns it more stable than the upper part, which allow them to conclude that the value of the constants, linear and torsional springs, of the bottom is higher when compared with the upper values, i.e. $k_{S1} > k_{S2}$ and $k_{T1} > k_{T2}$. The continuity and equilibrium condition at the interface of the liquid, inside the cylinder, are:

$$\begin{aligned} y_1(0,t) = y_2(0,t),\ y_1'(0,t) = y_2'(0,t) \\ y_1''(0,t) = y_2''(0,t),\ y_1'''(0,t) = y_2'''(0,t) \end{aligned} \tag{2.29}$$

This conditions allow them to investigate the relation of the normalized frequency ratio $f_r = f/f_0$, considering f_0 as the maximum frequency when there is no liquid inside, and the length ratio l_w/L in their experiments.

2.4.2 Relation with previous studies

So far the model presented show very general boundaries conditions, by controlling the variables, the model can be easily compared with the mentioned model. Taking that into consideration, a demonstration of this similarities was presented and is the following.

2.4.2.1 Clamped-free boundaries

For this condition, the values of the variables are considered to be $k_{S1} = k_{T1} \approx \infty$ and $k_{S2} = k_{T2} = 0$. When Chan and Zhang proposed this model to calculate the frequencies of a cantilever tube, partially filled with liquid mercury, the cantilever was clamped at the bottom and free at the top, and the transverse vibration was generated by using a hammer to knock the tube figure 2.8. If the values of the variables are replaced in the equation 2.27 the result

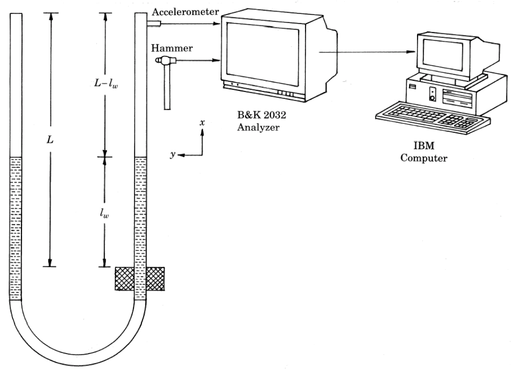


Figure 2.8: Clamped-Free Model
[18]

of this setup makes the boundaries conditions at their limits, $x = -l_w$ and $x = L - l_w$, to be as shown in equation 2.30, when comparing the results in the boundaries conditions they verify that they were the same as in the work from Chan and Zhang[18].

$$y_1(-l_w,t) = y_1'(-l_w,t) = y_2''(L-l_w,t) = y_2'''(L-l_w,t) = 0 \tag{2.30}$$

2.4.2.2 Pinned-pinned boundaries

For this condition, the value of the variables considered is $k_{S1} = k_{S2} \approx \infty$ and $k_{T1} = k_{T2} = 0$. In this model, proposed by Chan, Leung, and Wong[19], the study is made in a simply supported beam partially loaded, with distributed mass in both cases as illustrated in figure 2.9.

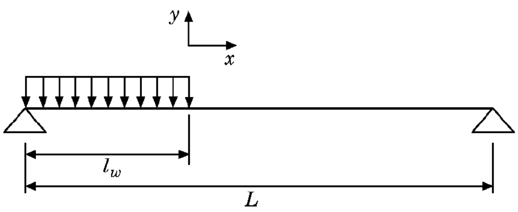


Figure 2.9: Pinned-Pinned Model
[19]

Once again, if the variables in equation 2.27 are replaced with k_{S1}, k_{T1}, k_{S2} and k_{T2}, the result in this setup will also match the boundaries condition from equation 2.31 at $x = -l_w$ and $x = L - l_w$, obtained in the work from Chan, Leung, and Wong[19].

$$y_1(-l_w, t) = y_1''(-l_w, t) = y_2(L - l_w, t) = y_2''(L - l_w, t) = 0 \tag{2.31}$$

2.4.2.3 Clamped-clamped boundaries

In this case, the value considered to the variables was $k_{S1} = k_{T1} = k_{S2} = k_{T2} \approx \infty$. The proposed model from Jacobs et al.[20], their study was made with an opaque capillary tube, as illustrated in figure 2.10.

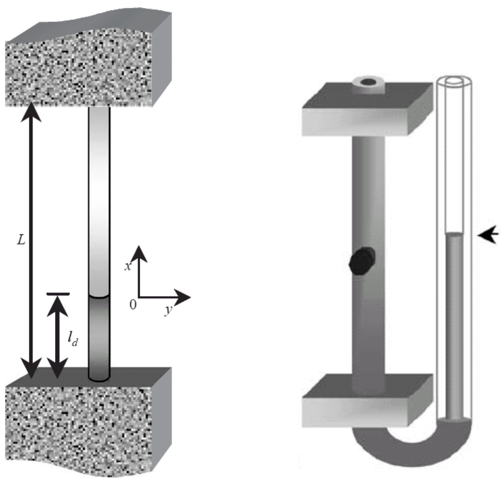


Figure 2.10: Clamped-Clamped Model
[20]

Following the same path of the previous two, the variables k_{S1}, k_{T1}, k_{S2} and k_{T2} were once again replaced in equation 2.27,and the results obtained equation 2.32 at their boundaries conditions matched results obtained in the work from Jacobs et al.[20]

$$y_1(-l_w, t) = y_1'(-l_w, t) = y_2(L - l_w, t) = y_2'(L - l_w, t) = 0 \tag{2.32}$$

2.4.2.4 Relation of Frequency versus Length

As a final comparison, the test between the relation of the frequency with the length of the liquid level was executed. For that, different values were attributed to linear and torsional spring variables, to allow the simulation of theoretical curves of the normalized frequency ratio $f_r(f_i/f_0)$ and length ratio $l_r(l_w/L)$. The values for each of the variables were chosen to be large enough to simulate the different boundaries conditions. As expected the results in figure 2.11 of Wu and Yang[8] were very similar with what was previously obtained [18, 19, 20], confirming what was mention in the beginning of this section.

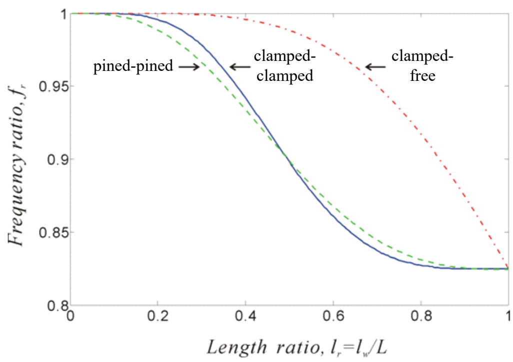


Figure 2.11: Frequency VS Weight - Theoretical curve obtained by for the different models [8]

In this relation is important to note that, when the cylinder is almost empty $l_r = 0$ the frequency of the vibration is the highest, in the opposite cases, when the cylinder is full $l_r = 1$ then the vibration frequency is archives the minimum value.

2.4.3 Experimental results

In the tests perform by Wu and Yang[8], their setup consisted in a hammer knocking in the lateral surface of the cylinder, that produces the transversal vibration, which is captured by a microphone,processed with a FFT algorithm. By continuously releasing gas and measure the produced vibration, and the correspondent frequency they obtained the relation observed in figure 2.12.

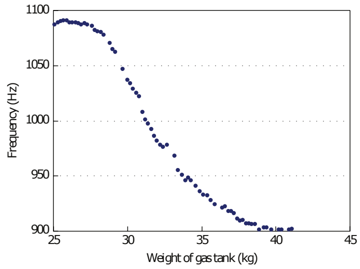
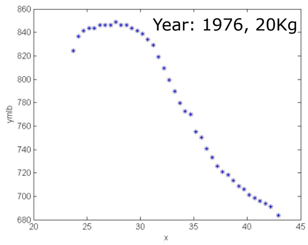
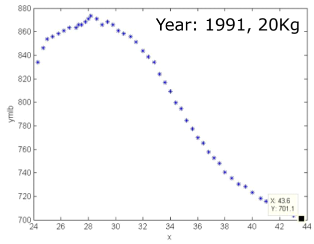


Figure 2.12: Frequency VS Weight - Practical curve obtained by
Wu and Yang

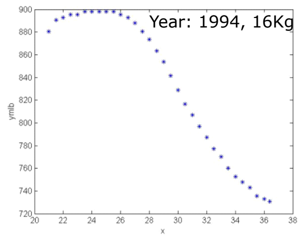
In the same way of their theoretical simulations, the relation between the vibration frequency and the liquid level is similar, the highest frequency correspond to the lowest liquid level, and the lowest frequency to the highest liquid level. One thing that is important to refer that is mentioned in their work is, this relation is constant for the different variety of LPG cylinders, but the frequency range of each also varies with the amount of gas that they can store, presented in figure 2.12, which means that the device must be adapted to the type of cylinder that is going to be used in.



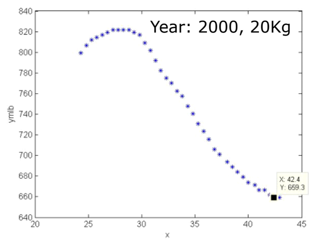
(a)



(b)



(c)



(d)

Figure 2.13: Different LPG cylinder to used to compare the relation between Frequency and Weight

[8]

A couple of years latter this work was followed by Wu et al., were they developed a prototype with the function of measure the frequency of the vibration, and thus the returning the liquid level of the LPG cylinder. The setup used and the test conditions were very similar the the previous work.

2.5 Vibration Sensors

To measure vibration is commonly used piezoelectric sensors or accelerometers. In the piezoelectric is possible due the small deformations produced during vibration, creating charges and thus a voltage change. In the accelerometer is usually measured the acceleration. In both cases the sensor needs to be in contact with the system, to measure the vibrations.

In the piezoelectric, the working principle of these sensors is similar, for the different constituent materials. The main difference between these types of sensor can be on their application, since the material influences in the resonant frequency of the sensors thus, limiting the frequency range of a certain application [23].

For the accelerometers is different, the working principle of the sensors varies. The most common, works similar to a seismometer, with a mass that moves with vibration. Attached to the mass is the component responsible to cause the voltage change, those are usually mechanical (figure 2.14), capacitive (figure 2.15) or piezoelectric (figure 2.16)[24, 25]. The downside of this sensor is usually their size, is some cases is much bigger than the MEMS accelerometer.

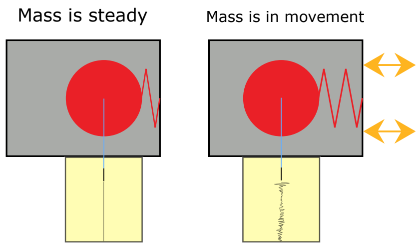


Figure 2.14: Illustration of the working principle of mechanical accelerometer

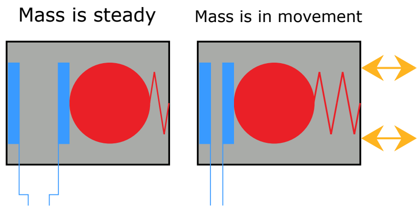


Figure 2.15: Illustration of the working principle of capacitive accelerometer

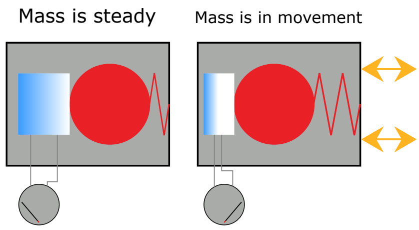


Figure 2.16: Illustration of the working principle of a piezoresistive accelerometer

The use of this type of accelerometer is very wide and commonly used in electronic devices, due their small sizes. They are a combination of a electrical and mechanical device, mounted in a silicon chip, which allows to be produced in small sizes.

The functioning of the accelerometer is simple, an electrode is between two other electrodes, with a air gap between them and insulation to prevent direct contact. The electrode in the middle is connected to a cantilever rigid enough to hold its position, but flexible enough to allow movement when the device tilts, the cantilever is used to measure the variance in capacitance with the other two electrodes. An illustration of their working principle is shown in figure 2.17.

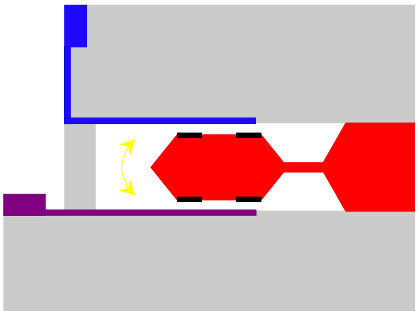


Figure 2.17: Illustration of the working principle of a MEMS accelerometer

This type of accelerometers brought important advantages, being their low cost and their small size the most important of it. On the other hand, the use of this devices for condition monitoring is restricted to a small bandwidth, restricted to a few kHz, and it cannot be used to in applications that require lower noise over higher frequency ranges [26, 27].

2.6 Concluding Remarks

There are several methods to measure the liquid level, this type of measurement is widely used in the different areas, with some of the methods used being presented along the chapter. From those, not all of them are suited for the intended application, since we are dealing with a closed and opaque cylinder, limiting the methods used in this application in specific.

From the ones that can be used in this situation, the one that seemed more suitable for this application, is based on the analysis of the vibrations produced, when stimulating the bottle with the hammer. For this reason, along the chapter were presented several concepts that are important to the development of the solution. The next step to take is based on these concepts and his purpose is to propose an approach to the problem, which will be explored in the next chapter.

Chapter 3

System Architecture

Considering the techniques presented in the previous chapter 2, the one used in the development of the prosed solution will be the Wu et al.[14]. Their stimulation technique and corresponding captured signals are similar to what is intended to obtain, but using a different sensor to measure the vibration from the hammers impact. The details of their approach both theoretical and practical, are specified in section 2.4. This allows to better understand the details of the system and how to approach it. With this consideration and the previously presented studies, this chapter will dedicate its focus, on the presentation of the main elements of the system, and briefly explaining their function, aiming to aid in the definition of a raw architecture for the system, and in the interaction between elements within.

3.1 System Elements

In order to develop a system that is able to properly measure and return an good approximation of the liquid level in the LPG bottle, it is necessary to identify the elements that must be present in the system.

Actuator

It is element responsible for the stimulation of the system. The main function of the actuator is to induce a transversal vibration throughout the system. In the presented work, two different techniques are proposed.

Sensor

The variety of sensors that can be used to measure vibration, not specific to this case only, is very wide. When choosing a specific one, it must be taken into consideration aspects like its practical application. More specifically, the dimensions of the sensor, its cost and the physical coupling between the system to be measured and itself, as an example. Other electrical aspects to be taken in consideration, are specific to the type of sensor itself and may vary from one to another.

The Processing Unit

The selection of the processing unit is quite important, since it is the "brain" of the entire system. Firstly, it is responsible for the interaction between sensors, actuators and with the rest of the system. It is also where the gathered data is processed and how the resulting information is returned to the user. In this particular application, it returns a data corresponding to the measured to the liquid level.

To achieve this, the processing unit must be equipped with different types of I/O ports, and, most importantly, the ADC, for converting the continuous time signal to a discrete signal. Besides the I/Os, the system must have the computational power to perform any type of mathematical tasks needed in the signal processing. This does not mean it must include dedicated DSP hardware, but it should be able to perform those tasks in a reasonable period of time.

Processing Architecture

As a signal is converted and stored in the processing unity, it is decomposed into two variables. The dependent is usually related to the amplitude of the signal, and the independent with the sample, and overall can be seen as the output of a sensor at a certain moment of time. While this data can be used to return visual information about the state of the sensor, it is not the only way. Usually, the frequency spectrum is used to identify patterns in the system's response that are not clear in time domain.

3.2 Architecture proposal

The system architecture consists in the union of the mentioned elements, as to obtain a device capable of measuring what is intended. The device itself should be attached to each LPG bottle, and be able to return to the user the level of liquid inside. The figure 3.1 is an illustration of the system's elements.

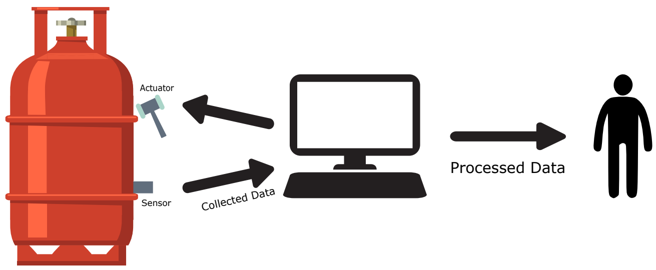


Figure 3.1: Basic architecture of the liquid level measuring device

As mentioned previously, the processing unit is responsible for the control of the system. Firstly, it is responsible for triggering the actuators which, in this case, corresponds to the hammer hitting the side surface of the LPG bottle, producing the vibration. In the mean time, the processing unit starts to convert the signal from the sensor, to and store the value. Then, the recorded data must be processed, in order to return to the user the desire information. Ideally, this procedure would occur once or twice a day, unless a manual measure was requested by the user. But for the purpose of this work, the main purpose is to get information, and be able to associate it to a volume of liquid in the bottle.

The chosen method to process the information, is through the analysis of the acquired data in the frequency domain. To achieve that, a FFT used to process the gathered data, and afterward associate it to a given level of liquid. A brief and visual description of the flow of how the process occur's in the processing unit is illustrated in figure 3.2.

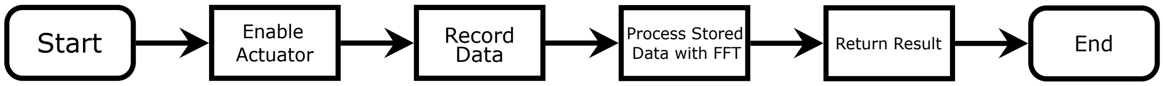


Figure 3.2: Proposed diagram for the device operation

3.3 Problem Approach

The approach to obtain a solution and hopefully a device capable of measuring correctly the LPG liquid level will be split into two main phases. The first one is the study of the behavior of the system to an external stimulation, followed by the development of the solution for this case. In both phases the hardware selection will differ. In the first stage, MatLab is used in the data processing. This system allows for easy manipulation of several of the system's parameters, like the maximum and minimum volume of liquid. Besides it allows to develop a solution without compromising its performance due to hardware limitations, due to established FFT algorithms.

The second stage will be divided in several smaller steps, so it is possible to individually address any source of problems. In this stage, the microphone will be replaced with two sensors. Besides, the hammer previously used continue to be implemented as a stimulation method, being later replaced with a solenoid, in order to automatically perform the trigger and posterior signal acquisition. Similarly, in the beginning, MatLab also used to process the data, but it is later replaced by a microcontroller. The reason for this is that it is easier to understand the type of signals acquired from the sensors and the proper way to process this data later, on the hardware implementation, avoiding skipping steps.

3.4 Concluding remarks

From the identification of the elements of the system, it is possible to define an approach to the problem presented, this chapter focuses exactly on that. Knowing those elements we are able to start to work in each element in order to integrate them in the final solution. The following two chapters will be dedicated to explore each element individually, they will be divided in two to separate the hardware/physical elements from the software.

Chapter 4

Hardware

This chapter consists in the identification of the physical components to use in the solution to develop, from the proposed approach. It will be explained the selection of each one of them and their purpose in the system. Beside this will be briefly explain the hardware developed for signal conditioning and to stimulate the system. In the end, will be presented some methods to attach the sensors to the bottle.

4.1 Selection

This section presents the selection process of each sensor and its purpose in the application. What were the criteria to select the sensors to measure the vibration, to process the data and to stimulate the system.

4.1.1 Microphone

With the intent of understanding what is the system response to an external stimulation, is necessary a method to record that response. The easiest way to do that is by using a microphone to capture the sound produced, when hitting the side surface of the LPG bottle. The choice to use as a microphone was the one embedded in the phone. By the time the study started, was the most practical option available. The phone itself is connected via USB to the computer, on which additional software was installed to allow access in real time to the microphone of the phone.

4.1.2 Accelerometer

As already mentioned in section 2.5, there are various types of accelerometers, however the choice depends on various factors. In this particular application is important that the accelerometer in use has a low cost and a small size, for the future application. With this in mind the choice declines over MEMS accelerometers, which are smaller when compared with piezoelectric accelerometers.

The type of MEMS accelerometers available is very wide, some of them started to be used in applications that usually uses piezoelectric accelerometers, like condition-based monitoring, structural health monitoring, asset health monitoring, vital sign monitoring and IoT. When selecting the accelerometer it is important to take into consideration some parameters, which are responsible to determine the category of the accelerometer, their application, the bandwidth and the range. Although there is no standard for the category on each accelerometer fits in, Analog has one document where they divide their products in different categories, with the type of application where each one can be used, featuring a description of the key parameters, that must be taken into consideration when selecting the appropriate accelerometer [28].

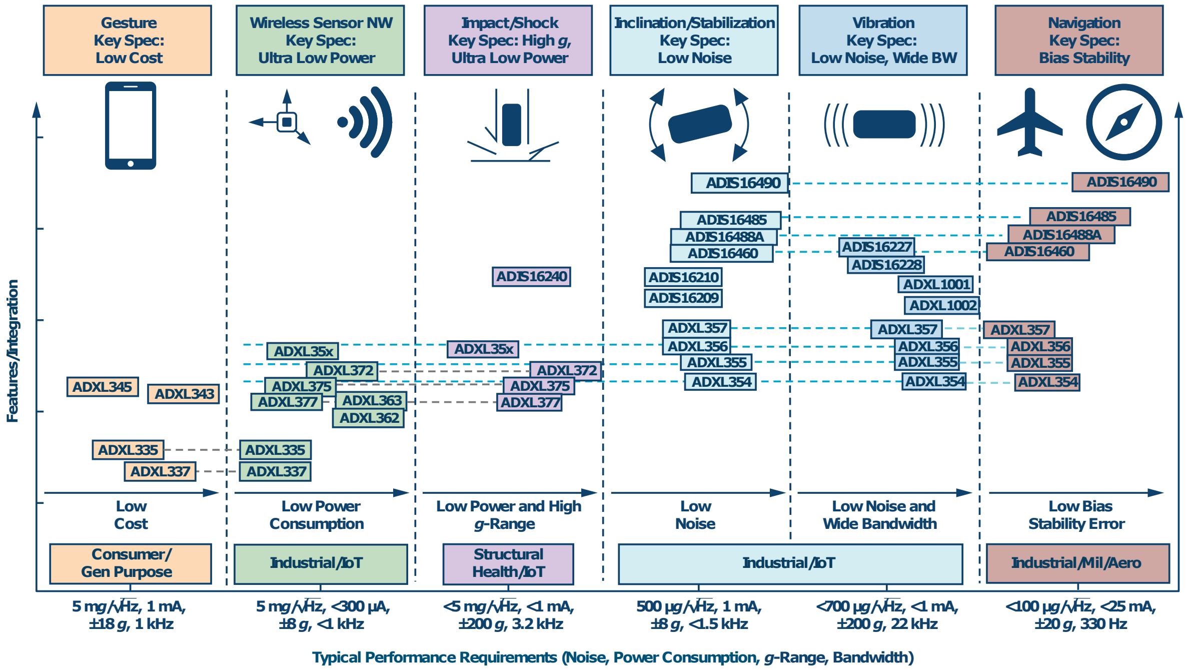


Figure 4.1: Application landscape for a selection of Analog Devices MEMS accelerometers

The MEMS accelerometers, from Analog Devices, are divided in two families, the ADXLxxxx and the ADIS16xxxx. The last offers different advantages when compared with the first, especially like a plug-and-play solution with features like factory compensation, embedded compensation and signal processing. This family has one of the features that has particular interest for the application, in this case the fact that it has signal processing on the accelerometer. On the other hand this family of products has a higher cost, which is not ideal if the final solution is suppose to be affordable. So it is necessary to define the key specifications of the accelerometer, in order to properly select one [28].

The final purpose is to have a cheap and portable prototype, that is capable of accurately measuring the vibrations and determining the liquid level. This implies that the bandwidth covers the spectrum of frequency on which the curve of the relation liquid level vs frequency is. With this in mind the key specifications are the low cost, low power and his bandwidth. According to the results obtained by Wu and Yang[8] shown in section 2.4 and the maximum frequency for a mechanical vibration, shown in table 2.1, it can be used an accelerometer with a Bandwidth close to 2kHz. Considering these specification, some models where chosen, that integrate this criteria, as follows:

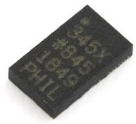
Manufacturer	Analog Devices				
Model	ADXL335 	ADXL337 	ADXL345 	ADXL354/5 	ADXL356/7 
Power Consumption	350µA	300µA	23µA	150/200µA	150/200µA
BandWidth	1600Hz	1600Hz	1600Hz	1900Hz	2400kHz
Noise spectral density	150/300 µg√Hz rms	175/300 µg√Hz rms	0.75/1.1LSB rms	22.5 µg√Hz rms	75 µg√Hz rms
Output type	Analogic	Analogic	Digital	Analogic/Digital	Analogic/Digital
Other			BandWidth is half of Output Data Rate		
Cost (aprox. cost for the chip)	3€	2€	13€	40€	46€

Table 4.1: Key specifications of MEMS accelerometers

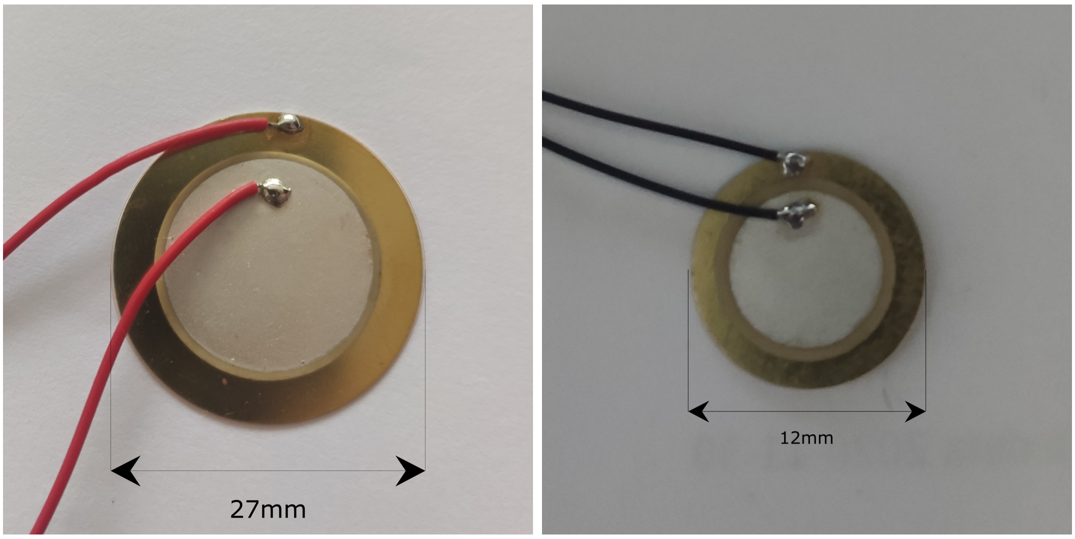
Although it does not accommodate entirely the specifications, but since it was already available for use, the choice fell to the ADXL335. This model offers a low power consumption of around 350μA, its bandwidth is adjustable with a single capacitor per axis, from 0.5 to 1600 Hz for X and Y axis and 0.5 to 550 Hz for Z axis. Beside this the accelerometer itself is very cheap, with a price starting at 3€. To properly acquire the data from this sensor and process it, it is necessary to integrate it with an amplifier circuit and a microcontroller, on which more details will be explained further ahead.

4.1.3 Piezoelectric

There are several types of piezoelectric constituents, a defining factor of the type of material used in the piezoelectric, is his application. The most commonly used in vibration measurement is PVDF as polymer and PZT as ceramic. This sensor produces charges according to the applied pressure and the voltage generated at the output is related with the amount of charges generated. In a electric point of view, this is a sensor with a high-impedance, therefore is necessary a amplifier circuit with a high input impedance and with a high SNR relation. For piezoelectric it is usual to use a charge amplifier, that already fills these requirements.

In the developed work, two different piezoelectric were used, with different dimensions, one with a diameter of 27mm and the other with a diameter of 12mm, as presented in figure 4.2.

The use of a piezoelectric is not only a cheaper option, when compared with the accelerometer, but also, allows to pursue a different approach. This is related to the stimulation technique of the system, that can replace the hitting to a different technique that uses the piezoelectric.



(a) (b)

Figure 4.2: Piezoelectric sensors used

4.1.4 Microcontroller

When selecting the microcontroller, it is important to have some specifications in mind, as in the perspective of a future implementation. Some are quite quite important, as the performance, the cost, as well as the power consumption. There is a large variety of products that most certainly would fit in these specifications. The selection of this it took in consideration those characteristics and fell to one from Texas Instruments. The model of the chosen, is the MSP-EXP430FR2433 and his characteristics are the following:

- 16-bit RISC processor with a clock frequency up to 16MHz;
- 15KB of program and 512B information FRAM, 4KB RAM;
- 8-channel 10-bit ADC;
- Four 16-bit Timers, 16-bit counter-only RTC;
- 32-bit Hardware-Multiplier;
- Two eUSCI_A, supports UART, IrDA and SPI and one eUSCI_B, supports SPI and I^2C;

Beside these characteristics, the microcontroller offers different low-power modes, that consume from several hundreds of microAmps to a couple of hundreds of microAmps, depending on the mode of operation of the microcontroller. Another thing in consideration, when selecting, is the fact that it is possible to run with a super cap. The performance in this case is not as important as it seems as it is not mandatory that an operation that would need to be performed must return the result to the user instantly, that means that the results not being in real time will not make much of a difference anyway if that was the case. There is also a 32-bit Hardware-Multiplier embedded, that reduces the use of CPU time to perform multiplications that would be required [29]. Associated with these characteristics, the price of this microcontroller is very appealing, starting under 2€.

4.1.5 Solenoid

Since the use of the hammer to hit the bottle is not practical and has inconstant results, a solenoid will be used with the intention of substitute the hammer. This way, is possible to stimulate the system automatically by powering the solenoid. With that purpose the SOL01002 was selected because this solenoid works with voltages starting at 5V and the other reason is due the fact that is a Push type, which means that when powered the shaft will move and produce the desired impulse.

Figure 4.3: Solenoid used to stimulate the bottle

The downside of using this model, can be the low impact force, it may not be able to produce a strong enough hit detectable by the sensors.

4.2 Design

This section is dedicated to explain how each circuit was planned to interact with the sensors in use, being important to the design what is the output of each signal. Before getting into details of each circuit, the resulting signal of each sensor and the consideration to further design the circuit will be presented.

4.2.1 Accelerometer

Considering that the accelerometer has three outputs, that are limited in frequency with a capacitor, the output used was the X axis with a bandwidth of 1600Hz, which is the maximum frequency.

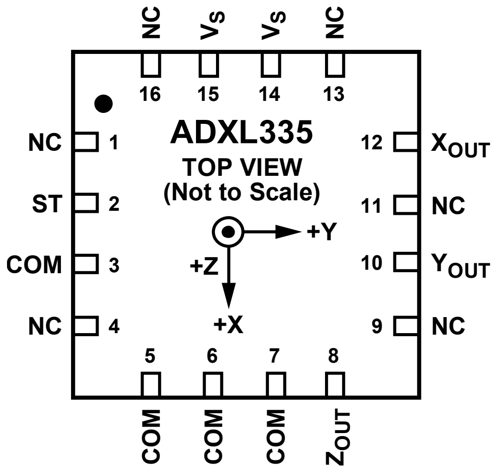
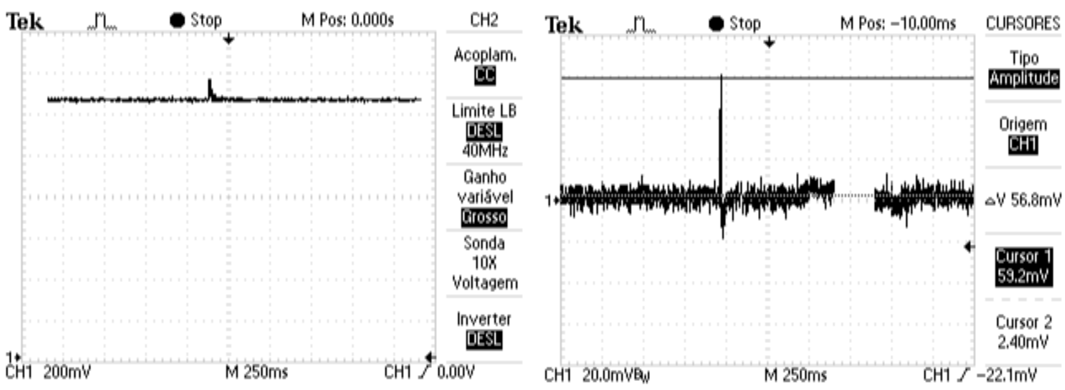


Figure 4.4: Top view of ADXL335

Considering the dot shown in the top view of the ADXL335, in figure 4.4, when mounting the accelerometer in the side surface of the LPG bottle, the dot is in the same position relative to the surface, on the top left corner. This way the output of the X axis measured, is around 1.25V, if the accelerometer is powered with 3.3V. Before designing the circuit to amplify the signal from the accelerometer is important to know, what should be the gain of the circuit. For that the surface of the bottle was hit with the hammer and the resulting output can be observed in figure 4.5a, approximately at the center of the image. In figure 4.5b is the same signal with zoom.



(a) Signal obtained after hitting in DC level

(b) Signal obtained after hitting, in AC

Figure 4.5: Signal obtained in the accelerometer after hitting with the hammer

Considering that the output of the amplified signal should be between the supply voltage range, that is from 0-3.3V, being the minimum of the input signal corresponding to one of the limits of the interval and the maximum to the other. If the amplifier circuit has an inverting configuration, the relation between the input and the output should be as illustrated in figure 4.6.

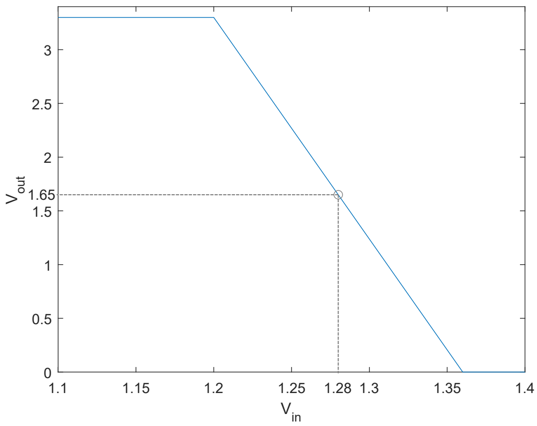


Figure 4.6: Desire relation between input and output of the amplifier circuit

The desire relation between the input and output from the figure 4.6, can be determined as in equation 4.1.

$$m = |\frac{\delta V_{Out}}{\delta V_{In}}| = |\frac{0-3.3}{1.3-1.2}| = 33 \tag{4.1}$$

In the equation, m corresponds to the gain of the circuit, in this case only concerns is, the manual stimulation of the system. When changing to a automatic stimulation, is probable that the gain needs to be adjusted, considering the same procedure.

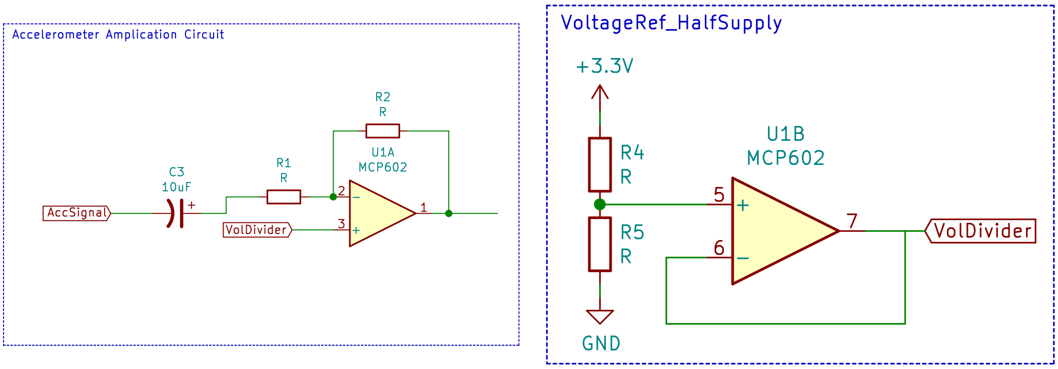
A problem when design a proper circuit for this application is related with his supply voltage. Usually a amplifier circuit with an OpAmp, the supply voltage is split, which means that the input/output signals are referenced to the ground. Since it will be used a battery or a super cap to power the device, limits us to a single supply.

In these situations, depending on the circuit configuration, the circuit may not operate for a determinate input voltage, since both input and output are referenced to the ground, thus the circuit will not function properly. In a dual supply voltage, if the supply voltages are symmetrical, the circuit is referenced to his midpoint, which is the ground. In a single supply it can be done in the same way, the signal can be referenced to half of the supply voltage, this is the simplest way to solve the presented problem.

For now, to prove the concept, the circuit in use can be solved in the simplest way. In some situations and in a future application it may be needed to develop a robust solution for this. For those situations TI provides a document that explains all the considerations that need to be taken into account and how to properly design the circuit for our application [30].

As mentioned, to quickly test, is considered an inverting configuration is used to the amplifier circuit and the signal is referenced to the midpoint of the single supply voltage of the OpAmp. As for the input signal, a capacitor is used in series to decouple from the DC level, this way the signal is "moved" to the midpoint between the supply voltage as referenced in the design from TI in their document, providing a schematic for both non-inverting and inverting configuration [31].

Figure 4.7 shows the circuit used to amplify the signal from the accelerometer. Although the output of the accelerometer is around 1.25V, using the decoupling capacitor we are able to move the signal to the midpoint of the supply voltage. The only thing necessary is to adjust the gain of the circuit according to the desire relation between the input and output signals.



(a)

(b)

Figure 4.7: Amplifiers circuit for accelerometer4.7a and Midpoint supply voltage 4.7b

4.2.2 Piezoelectric

As mentioned, piezoelectric sensors can be used in many fields, for sensing acceleration, vibration, shock or pressure. To what is related to acceleration or vibration, the piezoelectric will output a charge that is a function of his deformation/deflection. For the application in specific, the vibration produce, although is noticeable directly at the piezoelectric output, has a small amplitude which means that needs to be amplified to allow a distinct difference between what is actually the vibration and the output of the piezoelectric itself. To solve this, is important to properly design a signal conditioning amplifier circuit. Texas Instruments has a very clear document explaining how to design charge amplifiers for piezoelectric sensors [32], on which they explain different types of circuits for this application in specific, with the advantages and disadvantages. The simplest model of this type of circuit is as presented in figure 4.8.

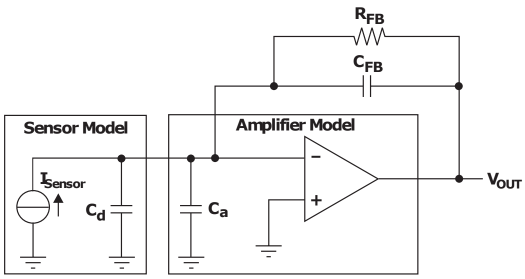


Figure 4.8: Charge Amplifier for signal conditioning

Two important things to consider is the bandwidth and the gain of the circuit. In the first case, the circuit functions as a High-Pass Filter which means that when selecting the feedback resistor and capacitance, their values must be selected to keep the cut off frequency low. The equation 4.2 can be used to define the cut off frequency.

$$f_{HPF} = \frac{1}{2\pi R_{FB} C_{FB}} \tag{4.2}$$

Usually, the value of the resistor in use is on the order of hundreds of megaohms and the capacitance should be low. The reason is due to the fact that in these circuits the gain is defined by the value of the capacitance, the lower the value, the higher the gain 4.3.

$$Gain = \frac{1}{C_{FB}}(mV/C) \tag{4.3}$$

Another factor that must be taken in consideration is the SNR, which needs to be maximized. For this circuit in specific, one way to achieve this is by increasing the value of R_{FB} as much as possible. To outline this and improve the SNR value, a differential charge amplifier is used.

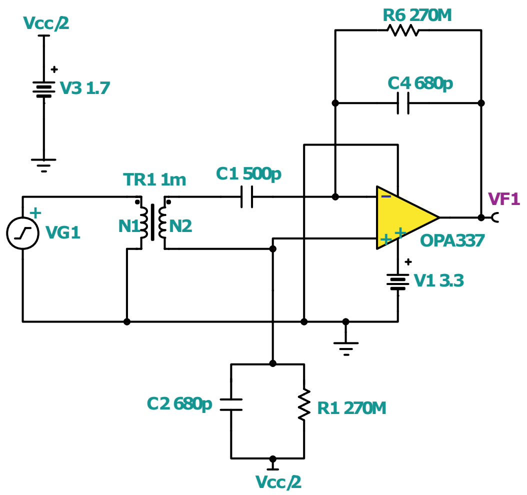


Figure 4.9: Differential Charge Amplifier for signal conditioning
[32]

Since this types of circuit are very sensitive to interference, the differential charge amplifier offers one advantage when compared with the single-ended circuit. In the single-ended circuit in one of the inputs is injected current while the other is connected to the ground, this will amplify the interference. In the differential input the common-mode signals will cancel each other.

For the practical application, the circuit in use will be as shown in figure 4.9. Considering the simulation that the document [32] presents, mainly those related with the SNR, this seemed to be the suitable choice for the application, since noise is a key aspect when measuring the signal, this is one way of reducing it. The difference in the circuit in use will be the components. The OpAmp in use will be the MCP602 from Microchip, as for the remaining components, considering the information from the document, it can be select the values of 1nF for the capacitors and 100MΩ for the resistors. With these values, the cut off frequency of the High-Pass Filter will be set at 1,59Hz and the gain of the circuit 2G(V/C).

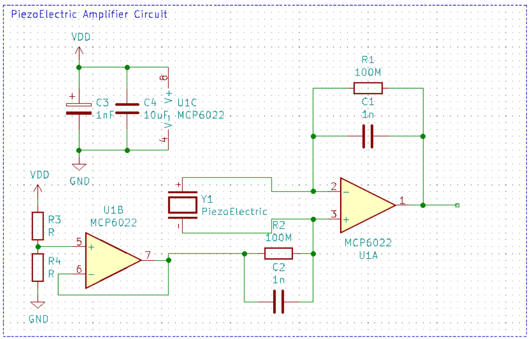


Figure 4.10: Differential Charge Amplifier Schematic

Note that, once again, beside being connected in differential mode, the circuit has on its positive input, a fixed input voltage of half the supply voltage of the OpAmp.

4.2.3 Solenoid

The circuit needed for driving a solenoid is very simple, it consists a MOSFET, a diode and a resistor as components. Is necessary to properly select the MOSFET, since the solenoid is active by a microcontroller with a high output voltage of 3.3V in the specified pin, is necessary to have a low threshold voltage from the gate to the source. The use of the diode in parallel with the solenoid is to forward the current when the MOSFET is switched off, is used as a flyback diode. In figure 4.11 is the schematic of the circuit used to drive the solenoid.

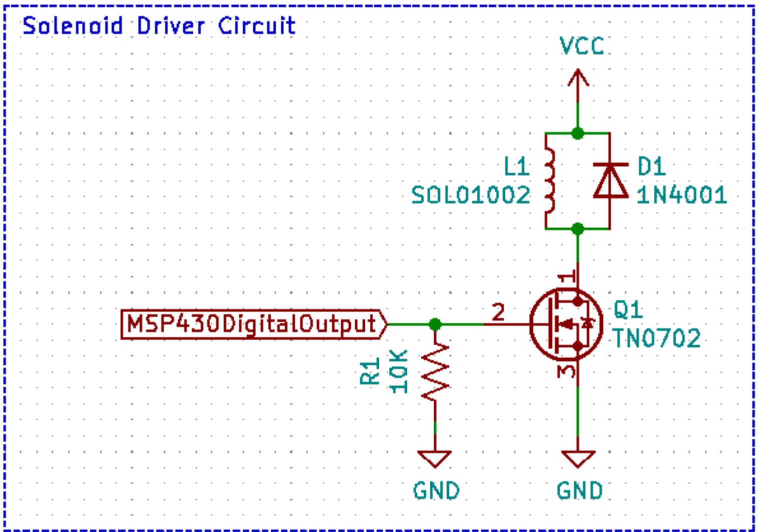


Figure 4.11: Circuit for driving the solenoid

4.3 Capture/Coupling

This section is dedicated to present several techniques for mechanically attaching the sensors to the bottle. The coupling of the sensor to the bottle plays an important role in how the signal is sensed. In the end different techniques where selected to attach the sensor in use, to use in the tests chapter.

4.3.1 Microphone

To position the microphone and acquire the sound produced when hitting the tank surface, the microphone was placed perpendicular to the surface of the tank and as close as possible to it. The figure 4.12 is an illustration of how the microphone is placed relative to the LPG bottle. In the practical setup, since it uses the microphone from the phone, the side of the phone where the microphone is, should be faced to the LPG bottle, usually the bottom part.

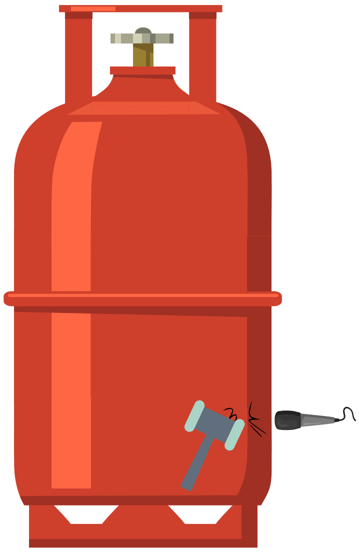


Figure 4.12: Illustration of the accelerometer mount with a load strap

4.3.2 Accelerometer

When using an accelerometer for sensing vibration, there are different methods to mount it to the desired surface. In the industry, where accelerometers are used to measure vibrations of motors/machines, the accelerometer is mounted to the surface with a screw, allowing good contact with the surface. But in the application pretended is not possible to use that method, since that would imply the change in the structure of the tank and the accelerometer in use is not ready for a screw mount. Although the best results are obtained with a screw mount there are other methods to mount the accelerometer.

One of the options is by using an adhesive, but in a practical mount the surface and the sensor would require different mounting bases, to avoid damaging the sensor and allow the sensor to be removed any time. Although this is practical to mount, it would also require that each tank already had the adhesive for the mount. The second option is a magnetic mount, offer a convenient mount if the structure of the tank is metallic. For this case it is advised that the magnet is in a separate piece, to avoid damaging the accelerometer. Magnets with a high pull strength are better in providing a good frequency response and a system with dual-magnet mount is good when the surface that the sensor is mounted on, is curve [33].

For the mount of the accelerometer in the LPG bottle, will be used a magnet mount, is the most practical mount for a future application. Although in a laboratory environment and for test effects it will not be the only type of mount used. The first mount method will be with a load strap, this will hold firmly the sensor against the wall of the tank, as will be used for the first tests. In figure 4.13 is an illustration of the sensor mount.

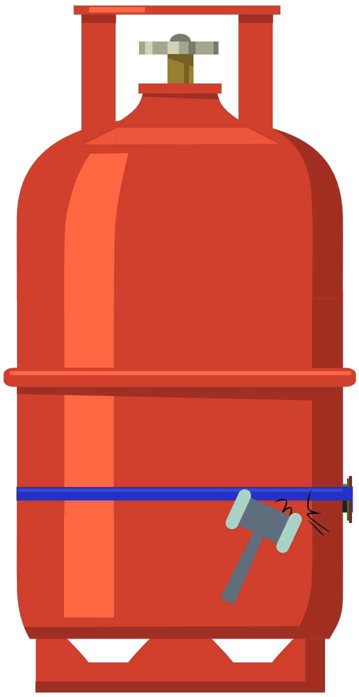
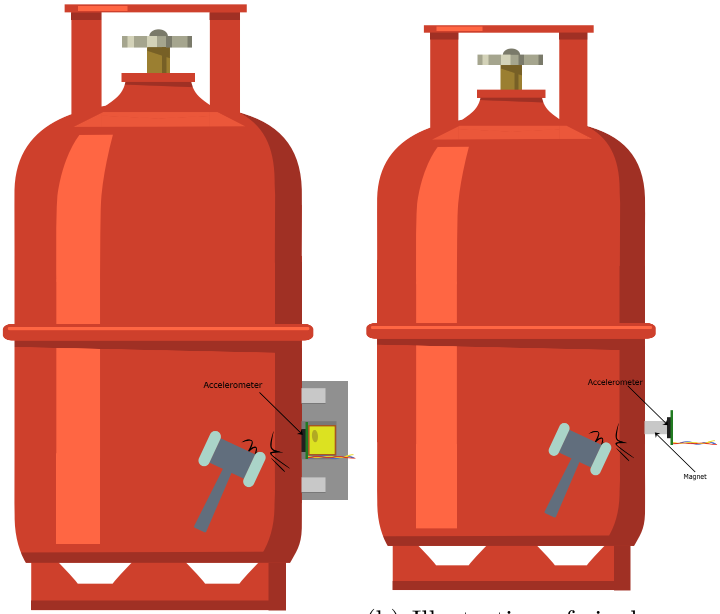


Figure 4.13: Illustration of the accelerometer mount with a load strap

For the magnet mount, there are actually two proposals, if by any reason one does not produce any results. In figure 4.14a is the ideal option, since it is less invasive for the accelerometer, for the reason mentioned above. In this case, a piece is design to be able to mount with two neodymium magnets at the top and bottom of the piece, this will push the piece against the wall of the tank. Between the two magnets is the necessary space for held the accelerometer, a sponge will be glued to the piece on one side and the other will be glued to the accelerometer. This will be slightly thicker than the piece in that way when the magnets attached the piece against the tank wall, the sponge will be compressed and the surface of the accelerometer, is expected to be firmly held against the tank wall as well.

In figure 4.14b, the mount is not ideal, since the neodymium magnet will be glued to the accelerometer surface for a god contact. This may result in better results when compared with the first option, but can damage the accelerometer, when attaching or removing the accelerometer from the tank wall.



(a) Illustration of dual magnets mount

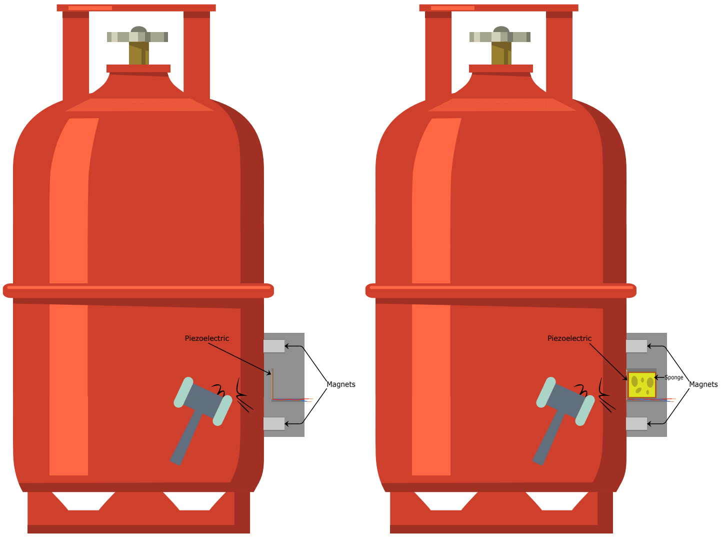
(b) Illustration of single magnet mount

Figure 4.14: Illustration of the accelerometer mount with magnets

4.3.3 Piezoelectric

TI provides a document [34], with considerations for mounting a piezoelectric sensor to measure liquid level using ultrasonic waves. Although is a different approach, the key aspect for mounting this type of sensors can be used as well to define how to properly mount them. What needs to be taken into account, according to the document is, if the sensors is to be mounted inside or outside, at the top or at the bottom and for last the temperature range that the sensor can handles before starts to degrading the piezoelectric capability. It is quite clear the first aspect, since is suppose to be a non-invasive solution, which means that should be placed outside of the tank. The second aspect is not relevant since is being measured the vibration, not being used ultrasound to measure the liquid limit where the wave is reflected. The third aspect is also not that important since is expected to have the sensor at environment temperature unless, and this can be seen as an exception, when the gas from the tank has been release for a long period causing the outer wall of the bottle to freeze. Beside the first, which was already a requirement, none of the others will have a significant difference. For the purpose of measure through the walls of the tank is required to have a good contact between the transducer and the mounting surface. In their application the glue the transducer directly to the surface of the tank [34].

Since the application is not ideal to have the transducer glued to the surface, the approach to have a good contact will be different, although the good results are not guaranteed. The figure 4.15 is the illustration of two different mounting pieces for the transducer.



(a) (b)

Figure 4.15: Illustration of the piezoelectric mount with magnets

Both pieces will stay held to the tank with two magnets, one at the top of the piece and the other at the bottom. In figure 4.15 a, the transducer is embedded in the piece, there is a slot in the middle, when the entire piece vibrates, the transducer vibrates with it. In the figure 4.15b, the coupling of the transducer is different when compared with the first one presented, the transducer is held glued to a sponge, and the sponge to the piece. The sponge is larger than the hole where the piece is glued in, so when the entire piece is attached to the walls of the tank, with the help of the magnets, it guarantees a good contact of the transducer with the wall. Since the sponge will press it against the wall and when there is vibration in the wall of the tank, it is expected to the transducer to capture the actual vibration.

4.4 Concluding remarks

The current chapter presented the hardware parts and the physical components of the architecture presented to the system. The selection/design of the elements was based in already known concepts of electronics, properly justified, in most of the cases, with existing documentation about the topic.

The presented elements of hardware were either produced or prepared, to use in the step that follow this, i.e. the selected sensors were attached using the mentioned coupling methods, and the schematics presented were printed in a PCB(Printed Circuit Board), to use to drive required components of the system. These elements will later be part of the tests set, along with the software elements that will be explored in the next chapter.

Chapter 5

Software

This chapter presents the necessary software, for the interaction between all the elements that are part of the setup used in all the stages until the implementation, with a brief explanation of how they work and what is their purpose in the setup. All the elements are not necessarily used at the same time in the setup and how they interact with each other will be presented in chapter 6.

5.1 Microphone

As the first measurements will be taken using a microphone, it requires a different approach to the type of interaction when compared to the future application, where a different sensor will be used to detect the vibration. The information is recorded from a microphone, in this case from a phone, which requires different pieces of software to allow the communication between the PC and the microphone. To obtain access and record the information from the microphone, since it is being used a phone, will be required additional software for that purpose. Both in the PC and the phone.

Also, on the PC side it is necessary to record the information from the microphone and store it as desired. The two components for this purpose will be the WOMic software as the bridge between the phone and the computer, and MATLAB to record the information from the microphone. The second software can also be used to later process the recorded data, helping the understanding of the obtained information.

WOMic

The use of the application and the microphone of the phone is simple, although the installation and the configuration requires some time. For that, it is required to install the software *WOMic* in both devices, which allows the use of the microphone of the phone in real-time. The software is available for Android and IOS and is responsible from the transmission of what is captured from the microphone. In the computer, the client application and a virtual device must be installed to proper use the microphone to perform any type of tasks and this connection can be made over USB, Bluetooth, Wi-Fi and Wi-Fi Direct.

In order to create a virtual microphone on PC corresponding to the microphone of the phone, the software is divided in three main blocks with different purposes. The *WOMic App* runs in the phone, samples the input of the microphone and transmits to the computer.

The *WOMic Client*, runs in the PC, connect to the app in the phone, and receive the data from the microphone, which is transmitted to the *WOMic Virtual Device* on which a real microphone device is simulated and provides the audio to any application or program in the PC, as illustrated in figure 5.1.

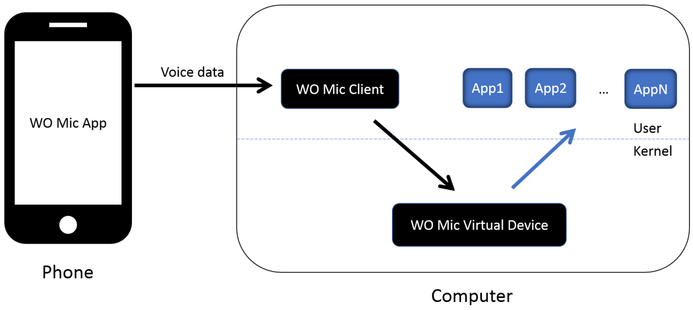


Figure 5.1: Flow of data in the components of the software
[35]

In addition, it is also necessary to install the drivers of the phone in use, if the connection is made over USB. To allow the access of the microphone in the PC via USB, the transport mode and USB option must be selected on the phone application settings, and then start the application. The PC client software must be initialized and connected to the phone in the following order >Connection>Connect... a new window will open, on which the PC must be selected as transport type and finalizing by pressing Connect. With this procedure, the microphone of the phone is available for use in the PC[35].

5.2 Microcontroller

To capture the signal from the sensor to later process and analyze, it is necessary to develop software required to interact with the sensors, actuators and communicate with the PC. It is also develop algorithms to process the data that are relevant for the application. The software used is briefly explained, with some details of their functioning and purpose.

5.2.1 Peripherals

Timers

In the configuration, two different timers were set, with the same configuration. One is used to measure the execution time of the algorithm and the other is used to set the amount of time that the pin that triggers the solenoid is high. In this case were used Timer0_A3 and Timer1_A3, in both, the counter mode of the timer is up, the division factor of the clock is 1 and they were set with a CCRx equal to 499 in compare mode, when the timer counter reaches this value will trigger an interruption. With this value an interruption will occur at every 500μs.

ADC

The LaunchPad in use offers a 10-bit ADC in the analog input pin 2 is selected. This input should be configured with the desire setting. To start, is mandatory to disable the digital port of the pin, by setting PySELx bits to HIGH it automatically enables the analog function of the port, although is still necessary to select the channel to conversion. The ADC will function in the sample and hold mode, using the timer from the ADC as the source of the sampling signal. The sample and hold period can be changed by software, to define the amount of clock cycles between each sample.

eUSCI

The eUSCI is used in UART mode to transfer data between the microcontroller and the PC, and is used during the tests phase to perform two types of tests: one to test the algorithm and the other to receive and send data to the PC. The eUSCI_A0 was selected for UART mode. In Transmission and Receiving, they were both set to work by polling with 115200bps of baud-rate, 8-bit, LSB first, no parity, no address and 1 stop bit.

5.2.2 FFT implementation

To process the signal captured from the ADC, a FFT algorithm is used. Two algorithms were considered to be used in the microcontroller, a Fixed-Point and a Floating-Point versions, this algorithm was discovered by Cooley and Tukey and bases on the complex DFT. The implementations used are based in FFT algorithm, and analyzing the Fixed-Point and the Floating-Point implementations side by side, they are quite similar. The main difference is in the data types used in each of the implementations, the fixed point can be adapted for the different types of signed integers, from 8-bits to 64-bits and uses a look-up table with the correspondent values of Sine and Cosine, used to calculate the real and imaginary in the frequency domain. This saves processing time, since is not necessary to calculate these values, while the algorithm is running. This implementation is less time consuming for the microcontroller. The Floating-Point version calculates the values of the Sine and Cosine, while processing the data. Since it deals with values like float or double, will require more memory and computational resources from the microcontroller, if the same is used in both cases. Both implementation can be found on a repository in [36, 37], for a implementation from scratch there is also possible to find pseudo-code for that [38]. The algorithms in use were adapted to fit in the purpose of the implementation for the microcontroller in use, as well as removed some options like the iFFT, which won't be necessary to use in this application. After performing the FFT algorithm in the input data vector, is necessary to calculate the magnitude of the resulting data, since the algorithm returns complex values. To obtain the magnitude of the data in frequency is a simple mathematical operation and is described in equation 5.1.

$$M = \sqrt{Real^2 + Imaginary^2} \tag{5.1}$$

5.2.3 Fixed-Point Square Root

For the application where the Fixed-Point is used it is convenient to only deal with integers, after performing the FFT is necessary to calculate the magnitude of the signal, relative to the frequency, since the data returned from the algorithm is complex. For that as known, is necessary to use the square root, several implementations of a Fixed-Point square root can be found. The implementation in use is an adaptation of the integer-to-integer version, from the repository [39]. In the used square root function, the input argument is a 32-bit value and the output a 16-bit value.

5.3 MatLab

This computational platform has various resources, with a lot of appliances. For the purpose of the developed work only a few simple functions of this platform. In a initial stage, is going to be taken advantages of some of their function to generate random signals, in order to test the viability and precision of the FFT algorithm that will be used in a microcontroller environment. This requires the use of some basic mathematical functions and the serial-port, the first is used to generate the random signal and the second to send the signal to the microcontroller via UART, so it can be processed and the resulting data can be compared with the original. On other sets of tests functions to record data from a certain audio input were used, to record the input of the microphone, each time that the LPG bottle is hit with the hammer. Beside this, the FFT function from the MATLAB is used to verify the response in frequency of the hit. Before the final application, is also need to verify the type of signals obtain in the sensors, after captured in the microcontroller the raw data is sent via UART to, once again, process them in the FFT function of MATLAB.

5.4 Level Identification

In chapter 2, we have seen that, when stimulated with a hammer, the frequency peak increases if the liquid level inside the LPG bottle decreases. If the conditions of the stimulation and measurement are consistent every time that they are performed, the results should be consistent for each liquid level. Considering this, it should be quite easy to develop a algorithm to measure the liquid level, basically the only thing necessary is to identify a frequency interval, where the peaks are, to reduce the searching time. As we will see it is not as simple as imagined, to determine the liquid level will be considered other factors like, the first peaks, the energy around the peaks and the one with the highest energy. In a first stage, before defining a frequency interval, all the spectrum must be considered, not only in the data captured by the sensors, but as well in the microphone.

Based on these notes, only after observing several samples of measured signals is it possible to properly define what is the interval and how to conjugate the characteristics of the spectrum, to define the algorithm to identify the liquid level.

5.5 Concluding remarks

The current chapter was used to present the software elements that will be used. Part of the presented ones, are not directly part of the processing/identification process, but are essential for the function of the software. This is the reason why they are mentioned and the important details from them are mentioned.

Combining these elements with the physical elements, mentioned in the previous chapter, we are now able to move to the final step, where we will be able to perform the necessary tests to evaluate the viability of each element of the defined architecture for the system. This will be done in the following chapter.

Chapter 6

Tests, Results and Analysis

This chapter explores the results of the practical tests, with the purpose of verifying if the application of these techniques is valid for a future product. For that, the setups, hardware and software were tested. Along this chapter is explained how each test was performed and the purpose of each of them, with the final test being the one of the identification validation.

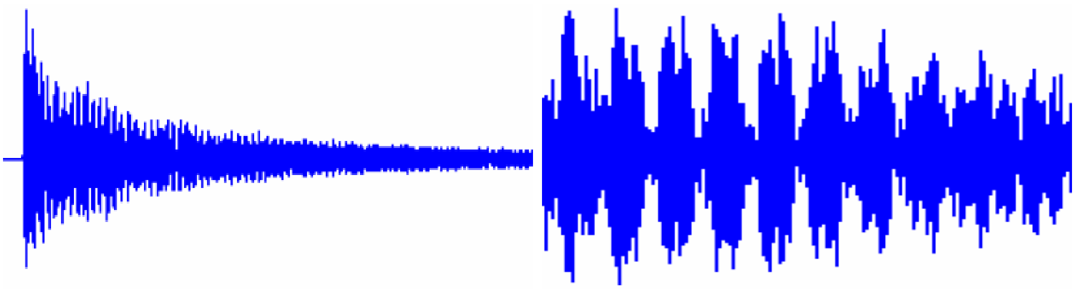
6.1 FFT Test

The purpose of this section is to test the effectiveness of the FFT algorithm implementation, mentioned in 5.2.2. One way to perform this test is recurring to random signals with known frequencies. In this way, is possible to compare the results from the implementation, in a microcontroller environment with the absolute frequency determined at when the generation of the random signal.

To try to perform the tests as close as possible to the type of signals that were expected to obtain, several aspects were taken into consideration, for that reason a small explanation of how the signals were generated will be given.

6.1.1 Signal Generation

To try to synthesis a wave form as similar as possible to the one resulting from the work of Wu and Yang[8] in figure 6.1.

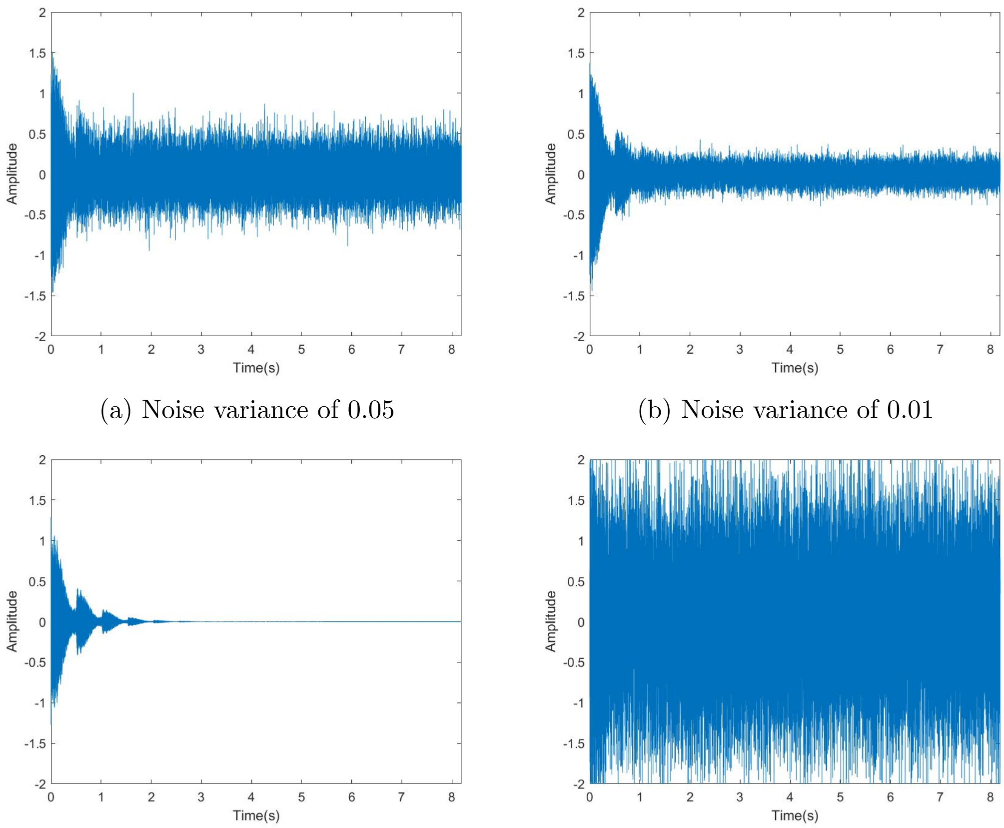


(a) Complete Signal (b) Fraction of the signal

Figure 6.1: Real signal
[8]

First is randomly define a frequency to be the dominant and a regular wave was generated, to create the decay effect the resulting wave is multiplied by $\frac{1}{e^x}$ being $x = 1$. To create the echo effect, the same wave is continually shifted and added, the amplitude of the wave decreases along the echo by increasing the value of x.

This procedure is then repeated to generate more waves with different frequencies and smaller amplitudes, in the end random noise is added with random variance, being at maximum half of the signal generated without any noise. An example of the resulting waves can be observed in the figure 6.2.



(a) Noise variance of 0.05

(b) Noise variance of 0.01

(c) Noise variance of 0

(d) Noise variance of 0.5

Figure 6.2: Example of signals synthetized with MATLAB with different noise variances

6.1.2 Tests

To test the effectiveness of the FFT algorithm, it was performed 1000 tests to verify the error obtained by the implementation. The tests were not exclusively performed with microcontroller. The same code for the Fixed-Point algorithm was used for the laptop computer implementation and the FFT function developed in MATLAB. This algorithm was used as verification test to guaranty that the dominant frequency of the signal was not corrupted with noise, which even MATLAB was not able to determined.

In a PC environment was implemented both FFTs, the Fixed-Point and the Floating-Point, in the microcontroller it was only possible to perform tests with the Fixed-Point since the other version exceeded the amount of memory needed to use the implementation. In each test a random signal was generated, as mentioned in 6.1.1, 512 samples of that signal were selected and converted to values between 0 and 1023, just like if it was converted by an ADC. After generating the signal, the dominant frequency is saved, to compare with the results, the samples are processed in MATLAB and a dominant frequency is obtained and saved as well. The samples used in MATLAB environment are saved, in order to be tested in both implementations in the PC environment and the obtained results are saved. To finalize the samples are sent to the microcontroller and processed and the result is sent back to the PC and saved6.4. After all the tests, the results obtained are compared with the original value used in the frequency, allowing to verify how the algorithm performs.

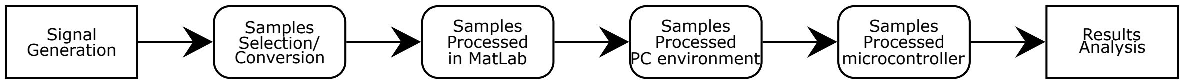


Figure 6.3: Flow of signal processing in different environments

Although the tests were performed in other environments, the test that is the most important is the one in the microcontroller. In the tests performed in the microcontroller is verified not only the viability of the implementation in this environment, but it is also necessary to know how long it takes to execute the algorithm in the microcontroller and what are the memory needs of the program. The program that executes the algorithm was built to start measuring the execution time of the FFT implementation right before it starts, and end it after calculating the magnitude of the resulting signal, while this occurs a variable increments in the timer each time a interruption occurs.

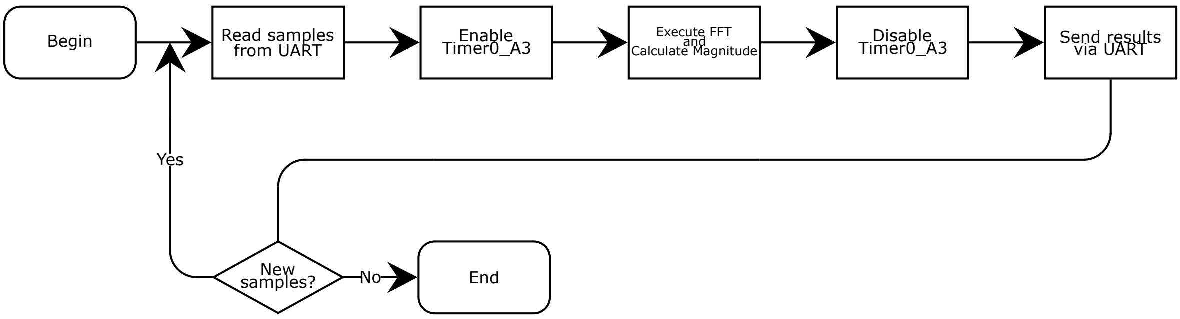


Figure 6.4: Flow of processing in the microcontroller

6.1.3 Results

The resulting data obtained from these tests, is the dominant frequency of each implementation with the FFT and the execution time of the algorithm. In the end the resulting dominant frequency from all cases was compared with the absolute frequency that was saved every time that a new signal was generated, the error obtained in each implementation can be observed in the table 6.1.

	Results				
	PC implementation		uC implementation		MatLab
	Fixed-Point	Floating-Point	Fixed-Point	Floating-Point	
Average Absolut error (Hz)	1.978	1.9659	2.534	-------------	0.40803
Max/Min Absolut error (Hz)	5	4.2	6	-------------	1.2
Average Relative error (%)	0.19845	0.197	0.25487	-------------	0.0408
Max/Min Relative error (%)	0.5637	0.47351	0.68886	-------------	0.13741

Table 6.1: Results of the execution of a synthetic signal in the different algorithms

It is evident that the results from MATLAB are better compared with the obtained. Comparing the Floating-Point with the Fixed-Point, in the PC implementation results, there is a slight difference between the two. For this microcontroller it was not possible to implement the Floating-Point algorithm. The error obtained in the Fixed-Point implementation does not increase significantly. These results show that the use of the algorithm in this dissertation practical implementation is expected to be precise for the application in question.

The results of the execution time of the algorithm can be observed in table 6.2. The number of ticks is due the fact that to measure the execution time, a timer was configured to generate an interruption every 500μs, incrementing a variable each time that happen. The execution time of the algorithm is the multiplication result of the number of ticks by the time each interruption takes to trigger. Taking into consideration that microcontroller has a small processing power and the embedded Hardware Multiplier has not been used, the about 3s it needs to process 512 samples it is to high, but acceptable under the test circumstances, since is not mandatory for the results processed in real-time.

		Execution Time uC Environment		
		Average	Minimum	Maximum
Fixed-Point	nº ticks	6159	6156	6161
	Time(s)	3.0795	3.078	3.0805

Table 6.2: Results of the execution of the Fixed-Point implementation in the microcontroller

6.2 Microphone Test

6.2.1 Signal Capturing and Tests

The analysis of the results obtained the microphone have special importance, to help understanding the viability of the frequency analysis for the different liquid levels. If valid which is the interval of frequencies that should be paid attention at and in which part of the bottle are obtained better results. After knowing this, is possible to perform a better analysis to the results from the sensors.

With this, four points were considered in the measurements identified in the illustration in figure 6.5. The points were all taken in the lateral surface of the LPG bottle. The bottle used is divided in two similar parts, by a welding joint in the middle. The measured points were taken in the bottom and the middle of each one of the the lower and top sections.

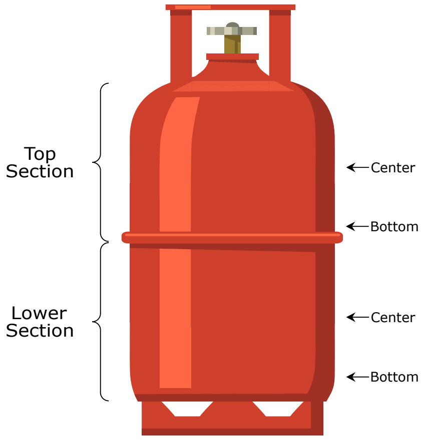


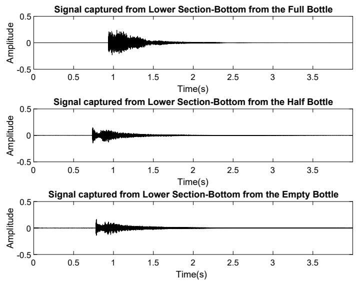
Figure 6.5: Measuring points in the LPG bottle

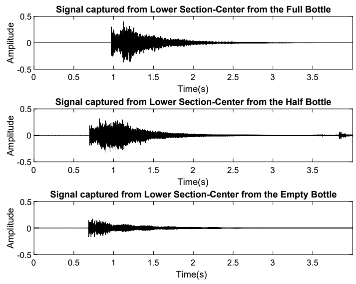
In each of the points illustrated, it was recorded the sound produced by manually hitting the lateral surface of the LPG bottle, for each of the 3 bottles available. The 3 bottles contained each a different liquid level, one full, one half-full and another empty. For safety reasons the liquid was water.

To capture, record and save the sound, some of the MATLAB capabilities were used for that purpose. The signal from the microphone was captured with a sampling frequency of 4kHz, configured in MATLAB, this value was set according to the considerations of section 2.3.3 and the maximum frequency from a mechanical vibration defined in table 2.1. To ensure that there was enough time between setting the PC to record and the manual hit the bottle. Each saved sample is around 4 seconds. The signal can them be processed and the resulting data analyzed.

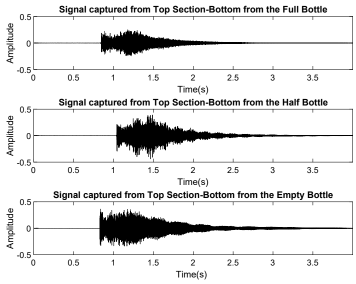
6.2.2 Results

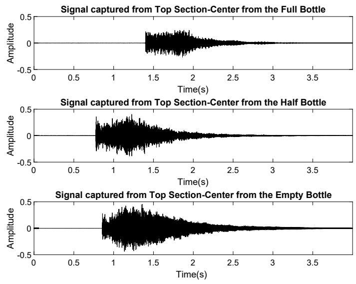
Several repetitions of the measurements were performed, to guarantee that the results obtained, follow a determined pattern and would not vary much from one measurement to another. In the figure 6.6 are presented the results from the different points of measurement in the different LPG bottles and in figure 6.7 the result from processing the same signals. Although is only presented one per point and bottle the remaining results were similar to the ones presented, the main difference for the remaining results can depend on how the hammer hits the surface of the LPG bottle and thus the signal can have smaller/bigger amplitude in the signals in the time domain, or peaks with higher/lower magnitude in the frequency domain.





(a) Lower Section, Bottom Position (b) Lower Section, Center Position



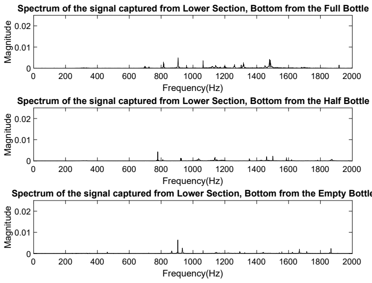


(c) Top Section, Bottom Position (d) Top Section, Center Position

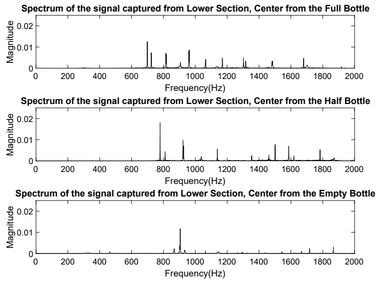
Figure 6.6: Captured signals in different locations in the LPG bottle

A example of how the hitting of the hammer affects the captured signal can be observed in the figure 6.6b, where the signal from the empty bottle has a smaller amplitude when compared with the signals captured from the full/half bottle and in the figures 6.6cd the same does not happen. For this reason, it is also necessary to find alternatives to manual hitting in the LPG bottle, first because the results would not be constant and second because in a final application it is not practical to do it manually. For now, the manual hitting was considered.

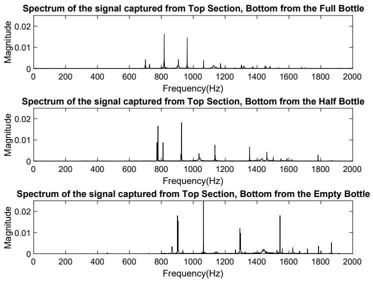
Even though the time domain is not considered to the detection of the liquid level, is interesting to observe the results obtained, beside the slight increase of the amplitude in the signal from the full bottle to the empty, the echo also increases in the same way as the amplitude, the other difference is how long the echo/oscillation occurs, once again from the full bottle to the empty the interval of time that happens increases.



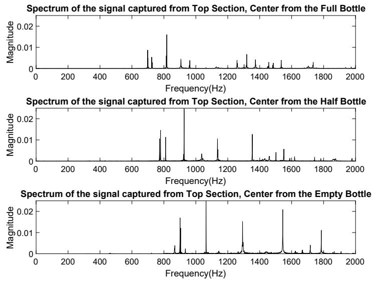
(a) Lower Section, Bottom Position



(b) Lower Section, Center Position



(c) Top Section, Bottom Position



(d) Top Section, Center Position

Figure 6.7: Processed Signals in different locations in the LPG bottle

After processing the obtained data, one example of the several measurements can be observed in the figure 6.7, one obvious conclusion is that the signal measured at the lower section in the bottom, in figures 6.6a and 6.7a does not result in a signal with the same amplitude in the time domain nor the same magnitude in the frequency domain, for analysis of the results this point was discarded. From the remaining points they both show some similarities, with the best results obtained in the top section in the center6.7d. Comparing the lower section in the center and the top section in the bottom, the results are slightly better in the second point mentioned, although for future measurements, the point considered will depend on the results obtained when changing the sensor in use.

To reduce the amount of time used in the identification of the liquid level, it is interesting to be able to determine a frequency interval to search, the limits of the interval should be determined by the response in frequency of a full and an empty LPG bottle. The results obtained from the points considered show that, is not identify for the full bottle any meaningful information in the spectrum below the $+/-700Hz$, for the other two bottles this value increases, for the bottle half filled the value shifts to $+/-800Hz$ and for the empty bottle to $+/-900Hz$, with this in mind the lower limit for the searching interval can be set around $+/-650Hz$, to have a margin. This shift in frequency from one bottle to another can be considered as a identification method, since the first peak occurs, according to the obtained results, between the $700Hz$ to $900Hz$.

From the first peak observed in the system response, the amplitude increases until it reaches the maximum amplitude, when starts to decrease, this will repeat once again. Is observed in the spectrum of the tree bottles, but more clear in the spectrum obtained in the measurements at the top section 6.7cd. Where the pattern starts to repeat, can be defined as the limit of searching. If observed, it starts to repeat around $400Hz$ after the first peak is identified, this can be used in combination to the identification of the first peak to check if after $+/-400Hz$, the identified peak has a higher magnitude than the previous, meaning that the pattern is repeating once again.

Another thing that is characteristic in the response to a stimulation of each bottle, is observed that the peak with the highest magnitude also shifts in frequency, in the interval of $+/-400Hz$ this value is approximately in the middle of this interval. For instance, for the full bottle the highest peak is around $800Hz$ and for the empty bottle is around $1100Hz$. Note that these results apply only for the results obtained at the top section and this identification method is the most inconstant, probably due the fact that the hitting is manual. Although this is not as certain as the mentioned before, these peaks also shift in frequency, which means that the searching for a peak in this interval is also valid for the liquid level identification, if combined with the other characteristics identified.

To sum-up, in the development of a method to identify the liquid level should be considered the following three characteristics:

- The interval on which the first peak will appear, between $650Hz$ and $950Hz$ approximately;
- The frequency were starts the repetition pattern, around $400Hz$ after appearing the first peak;
- The interval on which the peaks with the highest magnitude appear, between $800Hz$ and $1100Hz$ approximately.

6.3 Accelerometer and PiezoElectric Tests

In chapter 4, section 4.3 where presented several methods to mechanical attach the sensors to the LPG bottle. The purpose of this section is to test the sensors in order to find the most reliable mount method, to measure the liquid level.

In addition to the attaching method, it is important to verify how the bottle stimulation affects the system response and consequently the results obtained with the sensors in use. Considering this, in the performed measurements, the stimulation was always performed in two different ways, manually with a hammer hitting the surface of the LPG, and automatically with an impulse created with a solenoid. The measurements setups, for the different stimulation methods, will be explained and the results obtained for each one of them will be analyzed in this section.

6.3.1 Stimulation and Vibration Measuring

Even though in section 6.2 of this chapter was considered four different points to perform measurements, in this case it was contemplate only two, mainly due the fact that for the dual magnet mount it was not practical to place the printed piece in the bottle. From the measuring points presented in figure 6.5, was only considered the center points in both lower and top sections of the bottle.

The configurations used to sample the signal for the different sensors were similar, since both amplifier circuits have their output centered in half of the supply voltage. So, each one of the sampling methods used to examine the signals, refers to the both cases.

Manual Stimulation - After configuring all the necessary peripherals, an external interruption is set to be triggered by a push-button. When pressed it enables the timer to control the sampling frequency, and starts to read the value from the analog input. The read values are not stored right away, wait until a certain input value is reached. The value is set to be under/above 128 from the mid value, and is only passed if we knock on the bottle. From this point, 1024 samples are stored and then sent via UART to the computer.

Automatic Stimulation - Similar to the manual stimulation read, the peripherals are configured and the same external interruption is set. When pushed, the interruption will activate a timer that actuates in the solenoid, stimulating the impulse desire to stimulate the system. Right after stimulation the system, the timer responsible for the sampling, is activated and the conversion starts, storing 1024 samples, which are sent via UART to the computer.

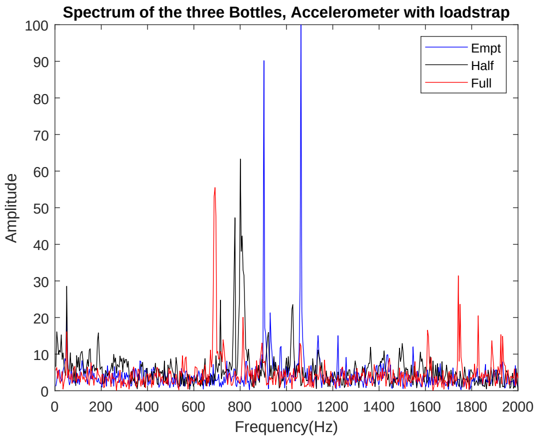
On the computer side, the data is received from UART and stored with MATLAB. In order to analyze the data acquired with the sensors, first is used MATLAB, which allows for a faster method to process the data and plot the results for the analysis. Before process the data with the FFT algorithm implemented in the microcontroller, a visual analysis must be performed to verify what are the characteristics of the processed signals, in each configuration, to later determine what is the proper method to identify the liquid level.

6.3.2 Results

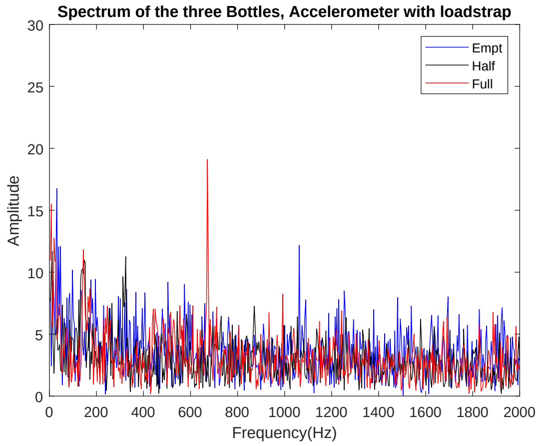
Several measurements were performed with the different sensors, in the different locations, configurations and stimulations. The considered aspects for the measurements, although already mentioned previously, where performed as follows:

1. The measuring Point
   (a) Center, Lower Section;
   (b) Center, Upper Section;
2. The Stimulation Method
   (a) Manual, with a hammer;
   (b) Automatic, with a solenoid;
3. The Sensors
   (a) Small PiezoElectric with the sponge;
   (b) PiezoElectric in a slot inside the piece;
   (c) Accelerometer with the sponge;
   (d) Accelerometer attached to the bottle with a magnet;
   (e) Accelerometer attached to the bottle with a load strap;

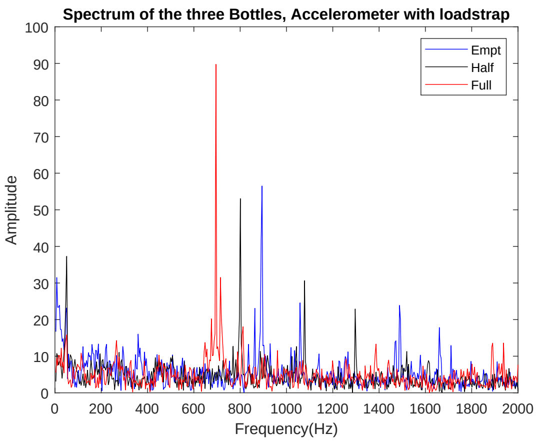
From the combination of all this aspects, the results obtained are the following 6.86.96.106.116.12.



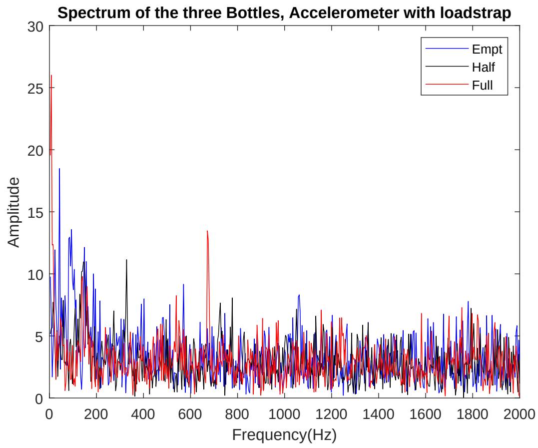
(a) Manual Stimulation at the center of the lower section



(b) Automatic Stimulation at the center of the lower section

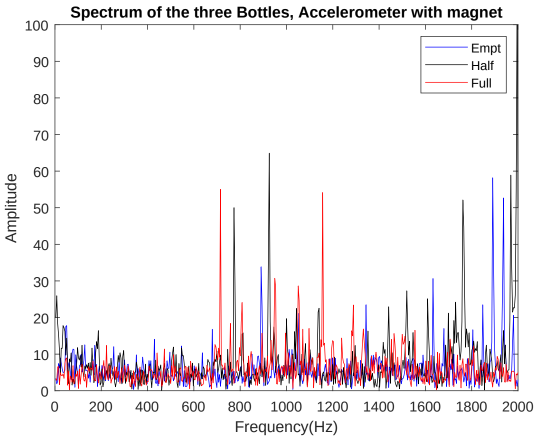


(c) Manual Stimulation at the center of the upper section

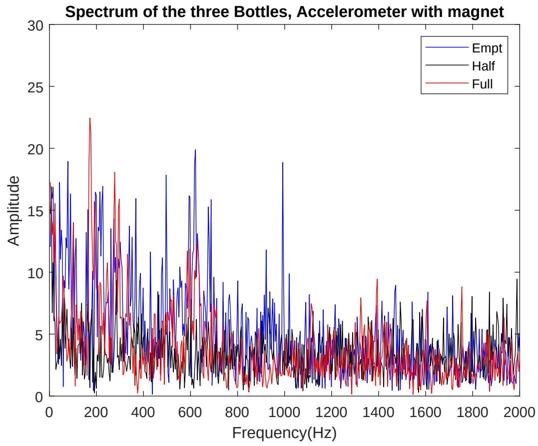


(d) Automatic Stimulation at the center of the upper section

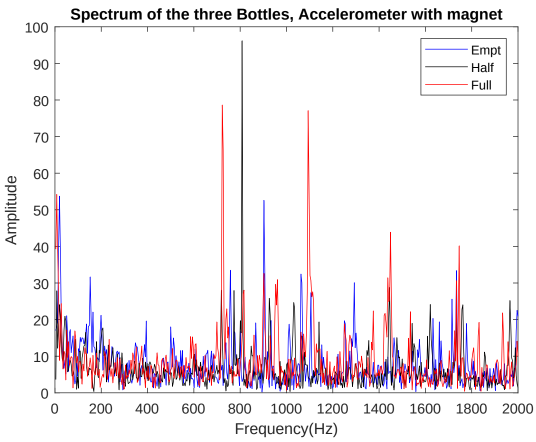
Figure 6.8: Accelerometer attached to the bottle with a load strap



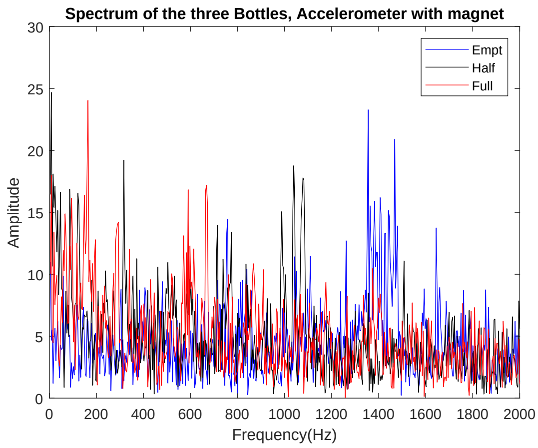
(a) Manual Stimulation at the center of the lower section



(b) Automatic Stimulation at the center of the lower section

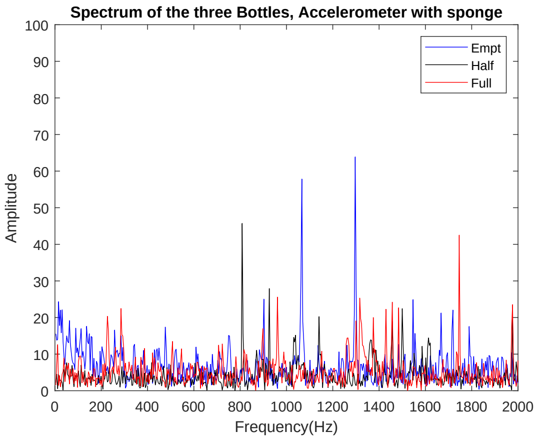


(c) Manual Stimulation at the center of the upper section

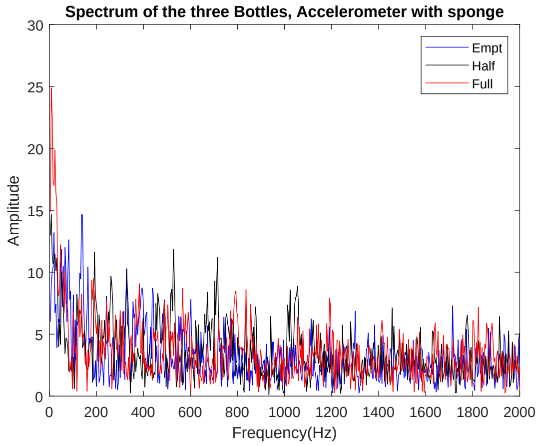


(d) Automatic Stimulation at the center of the upper section

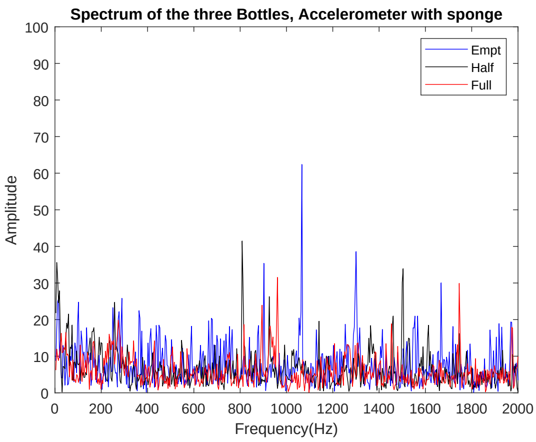
Figure 6.9: Accelerometer attached to the bottle with a magnet



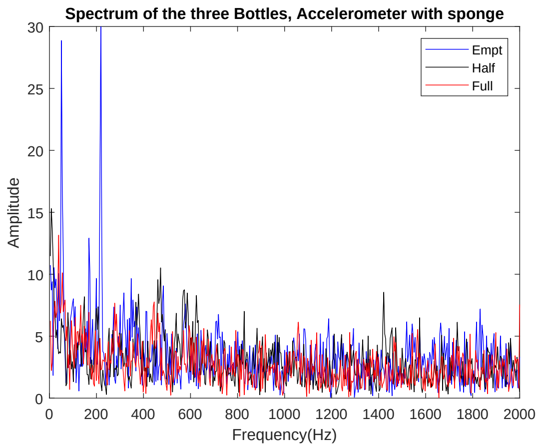
(a) Manual Stimulation at the center of the lower section



(b) Automatic Stimulation at the center of the lower section

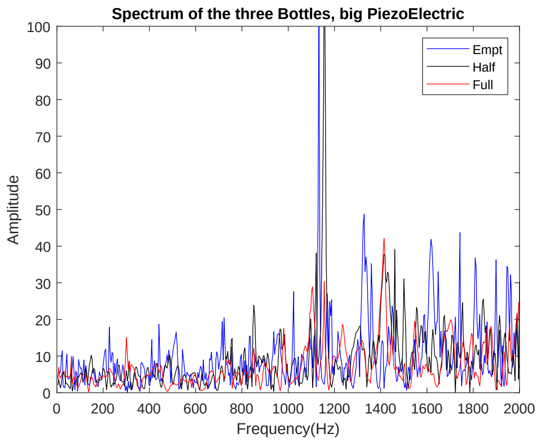


(c) Manual Stimulation at the center of the upper section

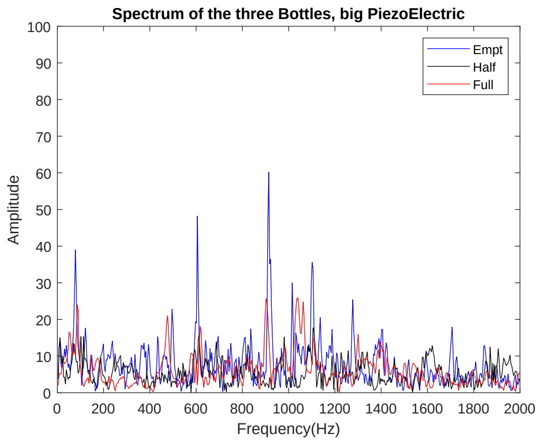


(d) Accelerometer attached to the bottle with a load strap

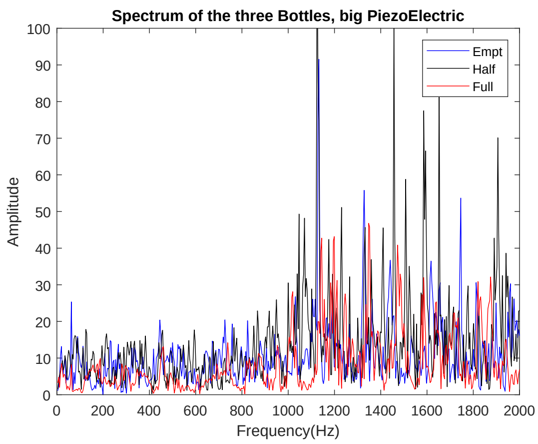
Figure 6.10: Accelerometer attached to the bottle with a dual mount magnet and a sponge



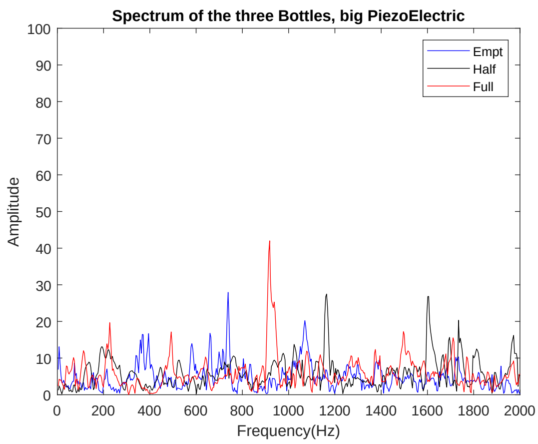
(a) Manual Stimulation at the center of the lower section



(b) Automatic Stimulation at the center of the lower section

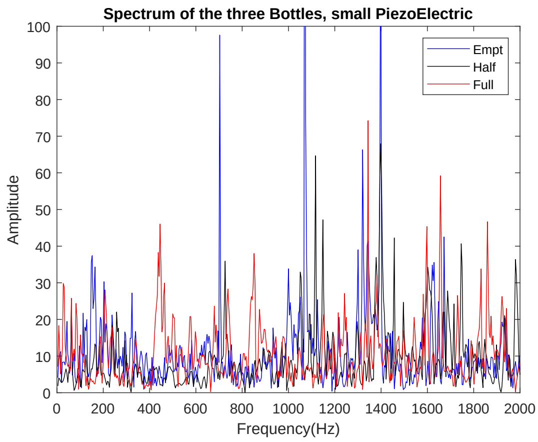


(c) Manual Stimulation at the center of the upper section

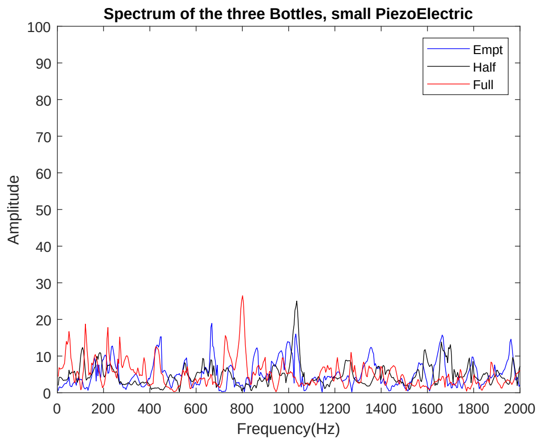


(d) Accelerometer attached to the bottle with a load strap

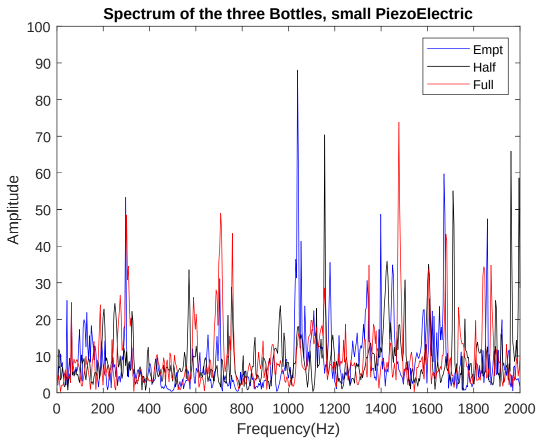
Figure 6.11: Big PiezoElectric inserted in a slot of a dual mount magnet piece



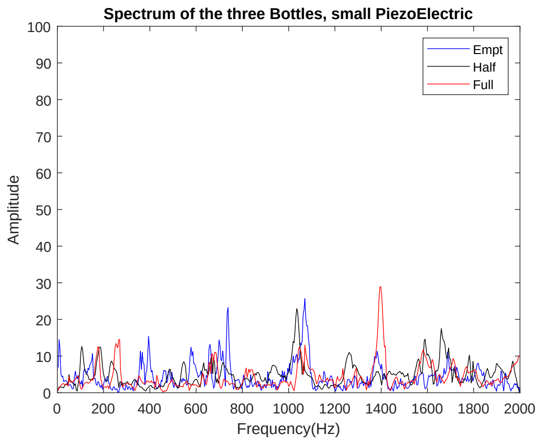
(a) Manual Stimulation at the center of the lower section



(b) Automatic Stimulation at the center of the lower section



(c) Manual Stimulation at the center of the upper section



(d) Automatic Stimulation at the center of the upper section

Figure 6.12: Small PiezoElectric attached with a dual magnet mount and a sponge

Note that, the presented results in the images above, are only referring to one sample of each bottle in each setup. In overall, at least 10 measurements in each point and setup were performed and most of the measurements were repeated more than once with small adjustments, at the hardware or software level. The presented results refer to the last series of measurements.

Analyzing all the results presented for the different setup, the use of the solenoid for the automatic stimulation was a complete failure, because none of the presented graphics on that setup provided relevant information about the liquid level. This lead to the conclusion that the stimulation with the solenoid is not enough to the accelerometer or the piezoelectric sensor detect the variation in vibration for the different bottles, as is going to be proved when analyzing the manual stimulation. This poor results may be due the fact that the impact caused by the solenoid is not enough to produce a visible vibration of the systems and the output end up being manly noise. Although the noise is a problem, this could be bypassed by averaging different spectrums of different measurements in the same conditions, resulting in a decrease of the noise, but without the expected results, the spectrum obtained still returned random values without clear information.

From the results obtained with the manual stimulation, the conclusions are the same as above, with two exceptions. One by using the accelerometer attached with a load strap, 6.8ac, and another using one magnet, 6.9ac. From these two, the most clear results are in the accelerometer attached with a load strap, where is visible a pattern between the three bottles. The first highest peaks occur between $+/-700Hz$ and the $+/-900Hz$, increasing from the full to the empty bottle, with a peak around $+/-800Hz$ for the half bottle. The same results are also visible with the magnet, but with the introduction of more peaks in between with smaller amplitudes, being reduced when averaging the spectrum.

Another aspect that is important to mention is that even though several measurements with the piezoelectric were performed, none of them presented relevant information, not even when averaging the spectrum. In the different tests, it was never clear the reason why the piezoelectric had not any valid results.

Considering the presented setups, only this two setups with better results are going to be used in future analysis, i.e the accelerometer with one magnet and with the load strap. That are the accelerometer with one magnet and the load strap. One final conclusion to take from all performed measurements, is how much the impact on the bottle affects the response of the system and thus the acquired signal with the sensor, as well as the importance of the sensor mounting in capturing the vibration.

6.4 Identification algorithm Tests

At this stage is important to move from the tests and analysis with MATLAB and verify if the algorithm implemented in the microcontroller returns similar results. For this, were considered the signals obtained with the microphone, the accelerometer with the load strap and the accelerometer with the magnet. The signals captured with the microphone were used because their spectrum was less noisy in the spectrum when compared with the other sensors. If the identification did not work with these signals, it would not work for sure with the remaining. Also, they were used as a way to define the limits of search in the identification algorithm, i.e. to define the interval in frequency to the identification of the liquid level.

6.4.1 Identification Steps

The first step was to obtain the spectrum of signals from the three different bottles, to define the interval in frequency in order to reduce the amount of time in the search and having more accuracy. In this case, the original signal was cropped and sent to the microcontroller for processing, returning then to the computer for analysis.

After this, an interval was determined and the identification algorithm was developed to find the liquid level. A threshold value is determined between the relation of the average amplitude of the spectrum and the highest peak, allowing for the threshold value to vary according to the amplitude of the signal. This threshold value is what determines if it is meaningful for the level identification, or if is just noise related.

Considering this threshold value and the limits defined, three main functions were created. The first one identifies the first peak, starts to look in the lower limit and goes until the upper limit. When the first value above the threshold value is found, the function stops and returns the value.

The second function considers a different limit, the lower limit is the same as in the first situation and the upper is set according to the cutoff frequency of the accelerometer, when testing with their values, otherwise is set until half of the sampling frequency. This function finds the highest peak in the spectrum, search for the entire spectrum considered and when ends, returns the value of the highest one.

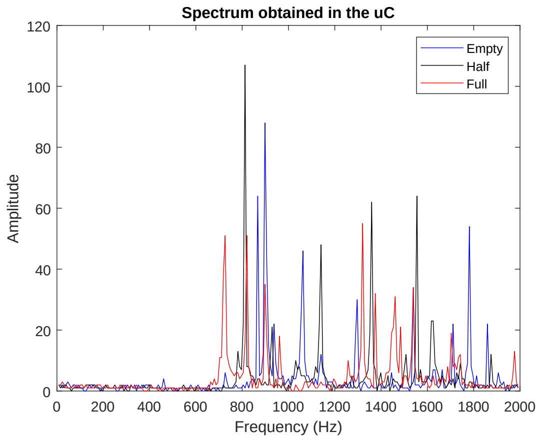
The third function was developed, to try to bypass one thing that was noticed in the second as most of the times, the highest peaks match with the first peak, which is due the inconsistency of the knock. When this occurs, near the frequency where it usually occurs, the spectrum has smaller peaks around it instead of a highest one. The purpose of this third function to try to find the consistency, by averaging around each peak, determine which one of them has the highest energy and return the value of where this happens.

Considering the functions for the identification of the liquid level, the signals obtained with the microphone, and the two configurations with the accelerometer, were sent to the microcontroller for processing and identification, and the results of the identification returned to the computer. On the computer side the results were plotted in order to find how well the identification functions performed.

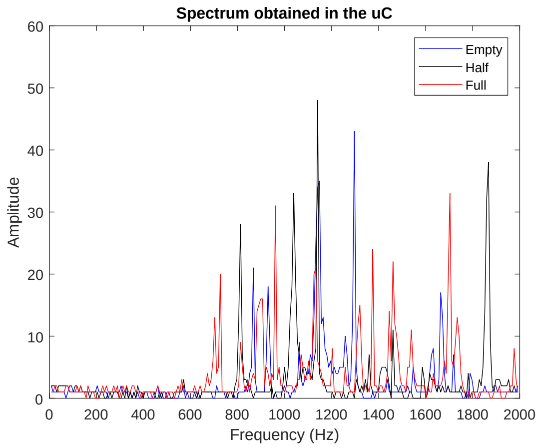
Is important to mention that the only reason the definition of the threshold value is this way is, since the manual hitting produces different responses, the algorithm needs to adapt to that variation. If the process was automatic this probably would not be necessary, as was expected to have consistency between all the signal captured to the same point.

6.4.2 Results

Before getting into the results obtained from the function created for the identification, the spectrum obtained from the processing with the microcontroller was analyzed, both for the microphone and the accelerometer and the results presented in figure 6.13.



(a) Spectrum of the samples obtained with the microphone, for the 3 bottles

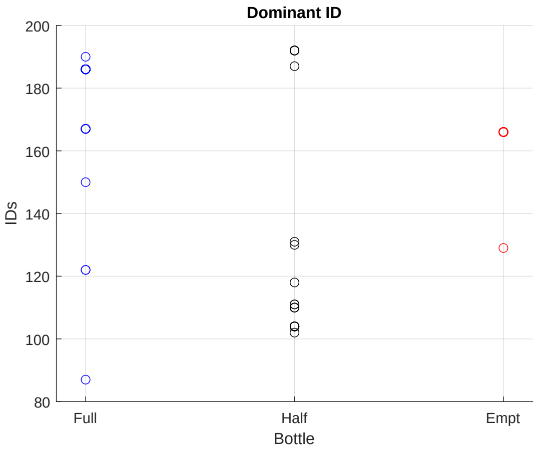


(b) Spectrum of the samples obtained with the accelerometer with the load strap, for the 3 bottles

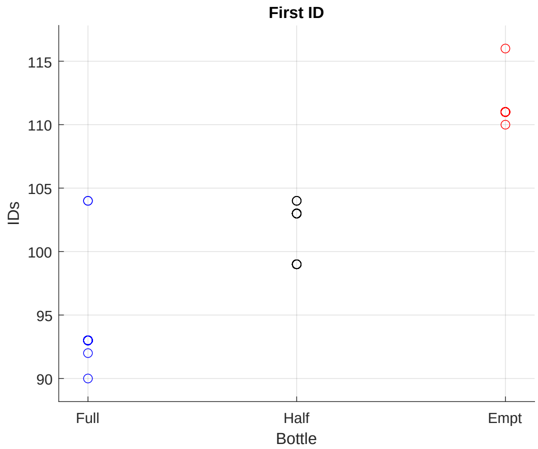
Figure 6.13: Spectrum obtained by processing the signals in the microcontroller

From the spectrum obtained for both cases it is visible that there are not any relevant information, for the level identification, below the 600Hz and in order to reduce the amount of time searching for the characteristics of the captured signals, this frequency is the reference to start. Also it is possible to observe a shift in frequency for the first peak of the measured signal for each bottle and this can give us confidence on the method to determine the difference between the three bottles, if the other methods are not precise.

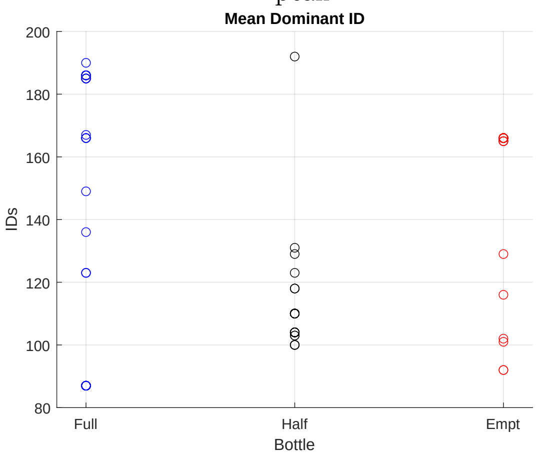
In the following graphics 6.146.156.16, is going to be presented the results obtained for the identification algorithms, for the cases mentioned previously. Is important to mention, that the results of the functions developed are not the frequency of each peak, but the ID in the vector of each peak, as in the future is irrelevant to determine if the liquid level is an ID or a frequency.



(a) Results for the search of the identify, of the dominant peak

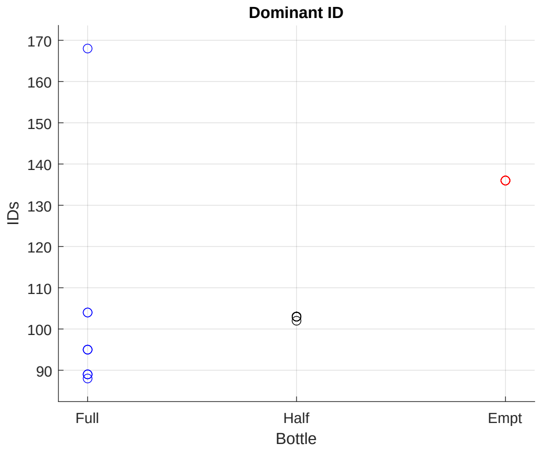


(b) Results of the search of the ID, of the first peak

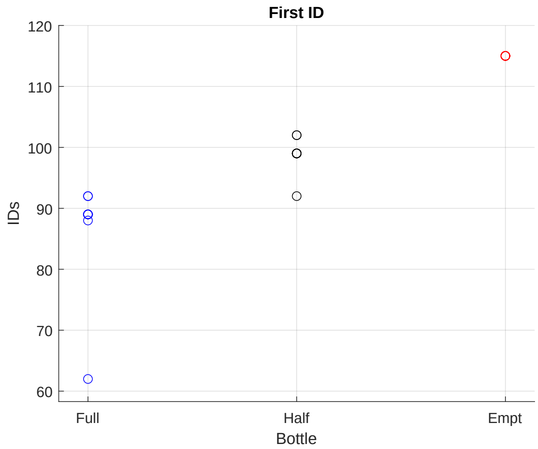


(c) Results of the search of the ID, of the mean dominant peak

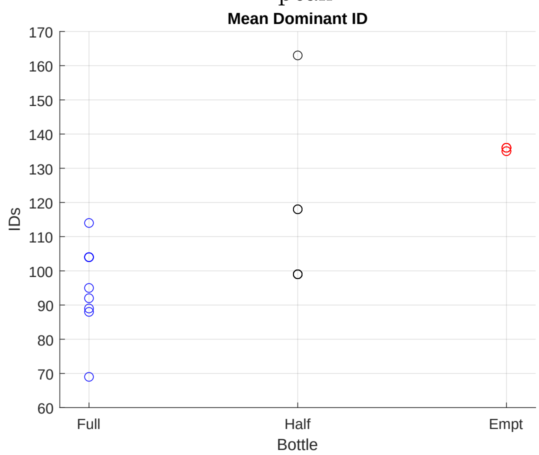
Figure 6.14: Results from the analysis of the signals obtained with the microphone, at the center of the lower section



(a) Results for the search of the identify, of the dominant peak

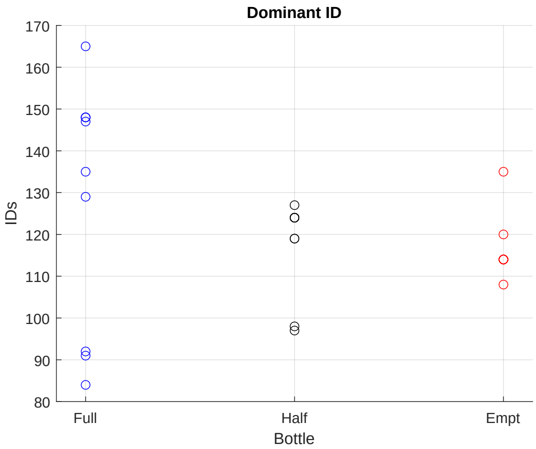


(b) Results of the search of the ID, of the first peak

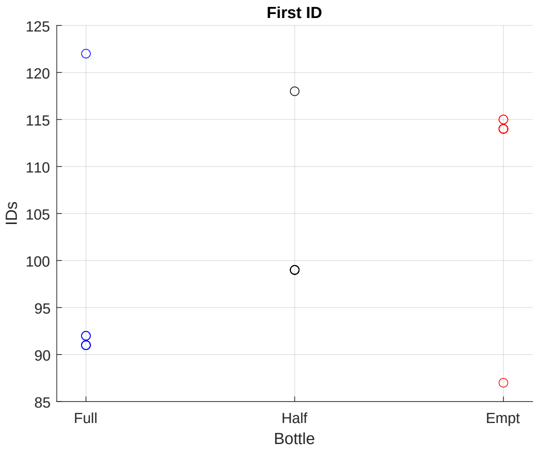


(c) Results of the search of the ID, of the mean dominant peak

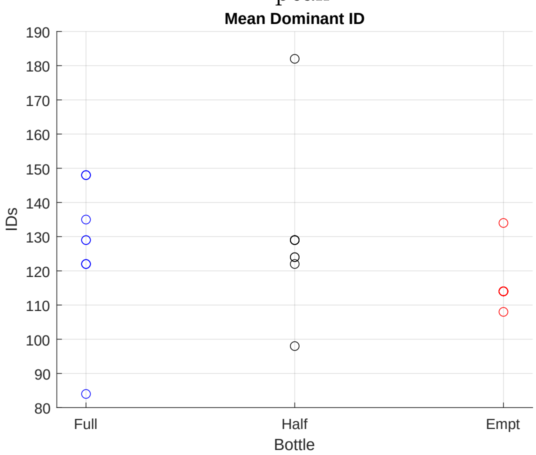
Figure 6.15: Results from the analysis of the signals obtained with the Accelerometer with the load strap, at the center of the lower section



(a) Results for the search of the identify, of the dominant peak



(b) Results of the search of the ID, of the first peak



(c) Results of the search of the ID, of the mean dominant peak

Figure 6.16: Results from the analysis of the signals obtained with the Accelerometer with the magnet, at the center of the lower section

Note that the presented results, in figures 6.14, 6.15 and 6.16, were measured at the lower section at the center, because the results at the upper section, in figures 123, were less precise when compared with the results presented. This also leads to the conclusion that the optimal point for the measurements should be at the lower section.

From the results obtained one thing is visible in all the tested setups, the most precise results were obtained in the search of the first peak. Although there are some signals that are an exception, it is possible to conclude that considering the circumstances, this could be implemented with the search of the first ID. One possible reason for the exception, may be due to the value of the threshold be variant between samples, and the stimulation is not constant. If it is possible to stimulate the system in a constant manner and strong enough to produce results similar to this, this problem will probably be bypassed.

Is quite satisfactory to observe that there is a pattern between the three bottles that allow us to identify each one of them, mainly in the identification of the first peak in the spectrum and this patter can be visible in figures 6.14b, 6.15b and 6.16b.If a consistency is found, the other two functions may also lead to more stable results, and the three functions combined can lead to more precise results.

From all the tests performed, in most of the cases the results obtained were satisfactory, although there are some considerations to do about them.

6.5 Concluding remarks

From the practical work developed and the results obtained and presented in this chapter, there is a good indicator of the path to follow in this work.

With the performed tests was possible to validate all the functions of the proposed architecture, even though not all return good results. The most important contributions from the developed work are, in first place, the validation of the FFT in the microcontroller environment. The identification algorithm, although not returning the best results, probably due the obtained signals, had a good indicator of the identification. This lead us to conclude that the stimulation and the signal acquired from the systems still need to be improved. These considerations will be explored in detail in the section 7.2.

Chapter 7

Conclusions & Future Work

7.1 Conclusions

The objective of this work was to develop a device capable of measuring the amount of liquid gas inside a LPG bottle, without using an invasive technique and suitable to be used in the bottles that are already available in the market. Beside the device for this purpose, the final solution should also be able to transmit to the distributor the measured value, so he would be able to properly plan a distribution route. That would imply developing a device, having local processing and communication resources, able to report measurements and be integrated in a IoT framework.

Considering the practical objective of this work, was firstly performed a background study, in order to analyze what type of solutions were already developed with a similar purpose, before proposing an architecture for the system. Taking into account that the main focus is in the development of the device to measure the liquid level, the background study was oriented to the research of techniques to perform the measurement of the liquid level and thus selecting the proper components to develop the work.

The starting point was to find information on how to acquire data relative to the liquid level, i.e. what type of techniques can be used for that purpose. A couple of methods were presented, each one of them, returning different types of information. The working principles range from measuring the weight, the vibration or using ultrasound. In the end the choice fell to the measure of the vibrations, mainly due the fact that this could result in a smaller and practical device.

The sensor requires the capability of measuring small vibrations produced when stimulating the system. For that were selected two sensors capable of measuring the vibrations. From the same background study it was found that there is a relation between the liquid level and the amplitude and center of the resonance frequencies, thus being necessary to process the data acquired to carry out a spectral analysis, being used for that purpose an FFT.

Taking into consideration the requirements of the system, was proposed an architecture, to acquire, process and return the liquid level. This proposal considers only a potential final product. Since it was not possible to know beforehand the effectiveness of the methods, the work was divided in several smaller steps, with the purpose of creating the foundations for in the future build the proposed architecture.

The steps consist in an initial study of the response of the system to a stimulation, to verify if the approach is feasible and if there is in fact a relation between the liquid level and the frequency of the vibration, using MATLAB. Then it was carried out the implementation of the FFT in a microcontroller device to assess the feasibility of the approach. After it, testing the sensors in order to find if they are suited for the application and to determine if the same relation level vs frequency is found. And finally the development of an identification method of the liquid level, based on the conjugation of the last two steps. If there are positive results from all these steps, a setup can be develop according to the proposed architecture.

The tests performed in the different stages of the practical part of this work revealed different and distinct results. The first two steps, although with different purposes, were the ones that revealed the best results. The first, that was intended to study the response of the system to a stimulation, resulting in the confirmation of the first hypothesis, show that the lower the liquid level the higher is the frequency produced in the vibration and the inverse for the maximum liquid level in the bottle. This test was also important in the determination of the variables to consider in the analysis in frequency, that were used in the tests that followed, mainly in the last two steps.

The second test, with the purpose to evaluate the accuracy of the implementation of the FFT, result in precise results for signals randomly generated, allowing to conclude that the processing of the signals captured with the sensors and processed in the microcontroller would also return viable data to determine the liquid level.

The third test, that focused on the study of the resulting data from the sensors, was the test that revealed the most disappointing results. Although there were positive results in the test that allowed the execution of the last step, these tests had different variables to consider and to control. The variable that revealed to be more difficult to control, in a potential application, was the stimulation. It was not possible to obtain meaningful results by stimulating the system with the solenoid. The only viable results were obtained by the stimulation with an hammer, which is not consistent enough nor practical, but was enough to the execution of the last step. Another variable that was difficult to control was related to the coupling of the sensors. By using the load strap and the magnet to mount the accelerometer, we were able to obtain acceptable results, for the mentioned tests. The other options did not reveal any useful results. This was the most difficult variable to control, even though there are some documents related to this topic, none of them had a similar application.

The last step was to evaluate if it was possible, considering the results of the processed data, to develop an algorithm capable of determining the liquid level. In this test, the results obtained for the identification algorithm were not as good as expected, but it was possible to determine it considering the first frequency peaks identified, as mentioned in the results analysis. Although there were acceptable results, this is also a step to improve.

In a final overview of all the work developed and the results obtained, it is possible to conclude that there are several aspects that influence the results, most of them already explored. There are other aspects that do not influence directly in the results, but in development itself. Considering all of this, it is important to mention that, even though the final purpose of the work was not complete, due to several constraints, it was possible to obtain positive results. These results can be used in a future work as a good starting point to the continuation in the development of the final solution, they reveal what can be explored and what can be discarded in a future. From the developed work and the problems faced along it, various suggestions emerged that will be explored in the following section.

7.2 Future Work

The work developed in the context of this dissertation, although allowed the formation of a foundation to the development of a device with the capabilities of measuring the liquid level, as intended, still has several aspects that can be improved and others that need to have a different approach to fully attain the objectives. In order to improve the already developed work and having in mind all the problems faced along the development of it, there will be presented some suggestions to improve the work developed so far.

The first suggestion is concerns the stimulation of the system, from the results is visible that hitting with a hammer return results, but is not practical, so in this case the suggestion would be to use also use a solenoid, capable to create a impact as strong as with an hammer.

The second suggestion, also concerns to the stimulation of the system, but is completely different to the one used, consisting in the use of piezoelectric sensors, emitting a sine wave with a certain frequency to stimulate and capture the response with another piezoelectric. By varying the frequency and correlating the emitted and received signals, is expected to determine the liquid level. This method was explored in chapter 2 in the work from Jahn, Ehrle, and Roppel[13]. As mentioned, is a completely different approach, but in their study proved to have good results.

One of the problems faced along the work is related with the coupling of the sensor with the bottle. Although some good results were obtained with the magnet glued to the accelerometer, the best results were obtained with the load strap, in a future application the use of a load strap end up not being a very practical solution. The suggestion in this case is to use a stronger neodymium magnet glued to the accelerometer.

In the hardware and the software developed there was always a problem related with the noise at the output of the sensors . For this case there is a suggestion that is widely used in signal processing for this type of situation and has a simple implementation, which is the use of moving average filters, this type of filters are optimal to the reduction of random white noise, while keeping the response. We will not get into details about these filters, for more information about the use of this filter Analog provides a document with a simple explanation [38]. The only downside of the use of this is related with the microcontroller in use, but there are some other aspects to consider, so this will be explained next.

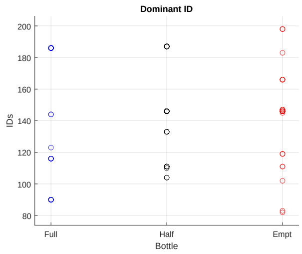
The microcontroller used was chosen due its low power capabilities, which end up being a very important aspect to consider in the future, for the development of the device. While developing, it started to be visible what can be a limitation of the microcontroller in use which is the execution time of FFT, an important aspect that can still be improved.

Other aspect related to it is the precision and the resolution of the level identification. The number of samples considered in the FFT was 512, which gives, according to the obtained results, a interval of around 30 samples between the correspondent id of the empty bottle and the full bottle, which results in a coarse resolution. The algorithm can be set to use more samples, thus increasing the resolution, but that would require more RAM space. The reason for not using more samples was due the fact that the available RAM is 4kB, which is enough to 2048 samples of 16bits, but there are other variables in RAM, that limit the amount of samples below that value, which is not ideal because the algorithm perform better with more samples. This would not be considered a constrain if it was possible to use the free space available in the FRAM, but the fact that the microcontroller in use does not have DMA(Direct Memory Access), this would also increase the execution time in sampling process and the FFT. Besides, to store data in the FRAM, is advised to disable interruptions, so it would not be possible to sample and store at the same time. The solution for this is the use of a microcontroller with more RAM.

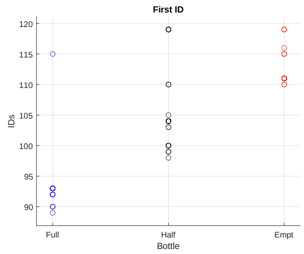
The last consideration is that all the samples collected along the development of the project are made available at the repository. The repository includes a document that contains information about each one of the experiments to allow in the future to perform tests without having to build any physical hardware B.

Annexes

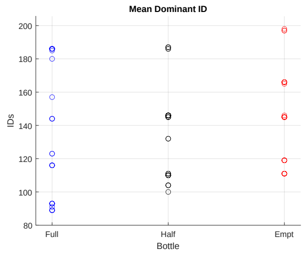
A Samples



(a) Results for the search of the identify, of the dominant peak

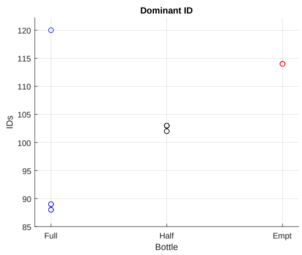


(b) Results of the search of the ID, of the first peak

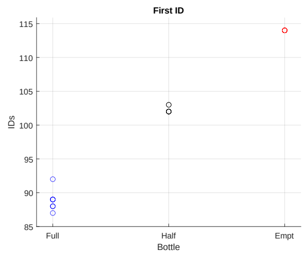


(c) Results of the search of the ID, of the mean dominant peak

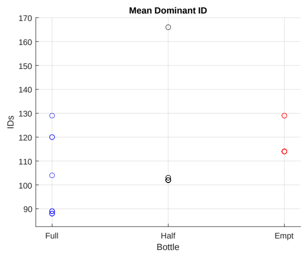
Figure 1: Results from the analysis of the signals obtained with the microphone, at the center of the upper section



(a) Results for the search of the identify, of the dominant peak

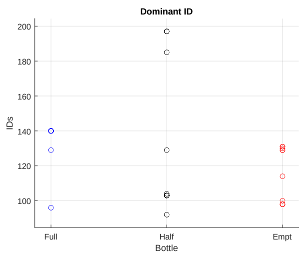


(b) Results of the search of the ID, of the first peak

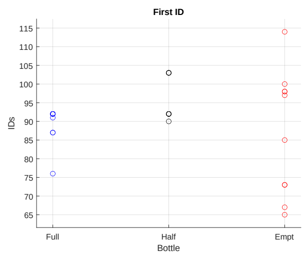


(c) Results of the search of the ID, of the mean dominant peak

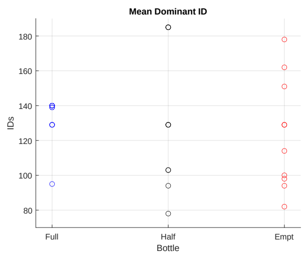
Figure 2: Results from the analysis of the signals obtained with the Accelerometer with the load strap, at the center of the upper section



(a) Results for the search of the identify, of the dominant peak



(b) Results of the search of the ID, of the first peak



(c) Results of the search of the ID, of the mean dominant peak

Figure 3: Results from the analysis of the signals obtained with the Accelerometer with the magnet, at the center of the upper section

B Collected Data

OneDrive Folder - https://uapt33090-my.sharepoint.com/:f:/g/personal/jacruz_ua_pt/ElqUfsKxBL9CsvtUOxGYkHoBP5eZepTHII8yvxcsprVG0g?e=qQF3wt

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