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Electronic Engineering

Automation and Instrumentation of a Workbench for Braking Tests

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Brasília, DF

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This work dedicated to all who seek knowledge and truth.

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"Science, my lad, is made up of mistakes, but they are mistakes which it is useful to make, because they lead little by little to the truth."

(Jules Verne, A Journey to the Center of the Earth)

Abstract

This paper aims to design the automation of a testbench for brake tests. There are already consolidated standards rules for brake system testing, this research project is focused with respect to *SAE J2522* regulation that addresses on brakes tests on passenger vehicles. The major focus of the project is to ensure a resilient solution for the testbench in order to make possible the acquisition of all relevant physical information and to automate the tests.

Key-words: Electronic Instrumentation. Brake Test. Automotive Systems Simulation.

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List of abbreviations and acronyms

SAE	Society of Automotive Engineers.
GUI	Graphical User Interface.
ABS	Anti-lock Braking System.
CKP	Crankshaft Position Sensor.
GPIO	General-Purpose Input/Output
SRAM	Static Random-Access Memory
EEPROM	Electrically Erasable Programmable Read-Only Memory
DIP28	Dual In-line Package 28pins
ISR	Interruption Service Routine
IC	Integrated Circuit
MCU	Microcontroller Unit
I^2C	Inter-Integrated Circuit
DAQ	Data Acquisition
PWM	Pulse Width Modulation.
N-MOSFET	N channel Metal-Oxide-Semiconductor Field-Effect Transistor.
LPF	Low-Pass Filter.
TVS	Transient Voltage Supressor
OPAMP	Operational Amplifier
USB	Universal Serial Bus
UART	Universal Asynchronous Receiver-Transmitter
ESD	Electrostatic Discharge
EMI	Electromagnetic Interference
PCB	Printed Circuit Board

RFI	Radio Frequency Interference
DAC	Digital-to-Analog Converter
ADC	Analog-to-Digital Converter

List of symbols

Pa	Pascal: Unit used to measure pressure.
kPa	10^3 Pascal.
MPa	10^6 Pascal.
°C	Celsius Degree: Unit used to measure temperature.
kph	Kilometer per hour: Unit used to measure speed.
m	Meters: SI unit used to measure distance.
cm	10^{-2} Meters.
s	Seconds: SI unit for measuring time.
ms	10^{-3} Seconds.
hp	Horsepower: Unit used to measure power.
kB	KiloBytes: Used to measure memory size.
V	Volts: SI unit for measuring electrical potential.
mv	10^{-3} Volts.
Ω	Omega: SI unit for measuring electrical resistance.
A	Ampere: SI unit for measuring electrical current.
mA	10^{-3} Ampere.
g	Earth gravity acceleration ($9.8m/s^2$).

Summary

1 Introduction

With the advancement of technology cars are leaving the factory each time with more power for more affordable prices. In 1995 the best-selling car in Brazil (HERNANDES, 2017) *(Volkswagen Gol Plus 1.0)* had 49.8hp of maximum power and brand-new would accelerate from nought to 100kph in 22.4 seconds (CNW, 2017b) while sales champion of 2015 *Volkswagen Gol 1.0* had 76hp of maximum power and could do the same challenge in 13.3 seconds (CNW, 2017a), almost half the time from the previous. Interisting fact is even though the latter is 20 years younger, both cars have similar brake systems, disk brakes in the front and drum ones in the back. To make things worse, the younger one does not have ABS *Anti-lock Braking System*, which only became mandatory for cars manufactured from 2014 and beyond according to brazilian regulations.

Although this is short analysis has only two subjects it brings up that maybe manufactures and customer are too focused in performance rather than safety. Of course for a standard customer it is obviously hard too evaluate the breaking performance of a vehicle upon buying it. Governament and legal authorities have been creating strict regulations for manufactures too follow in order to ensure that cars have a higher standard of safety.

Brake systems are extremely important in terms of safety because even though cars nowadays are required to have a higher perfomances in crash tests it is always favored too avoid collisions.

Brake tests with full scale vehicles are expensive and this somehow makes extensive testing unfeasible. Also the time required for each test might be a constrain. It is a possibility that maybe using small scale tests it would still be possible to provide relevant information about quality and performance of brake systems with lower costs and reduced time. Small scale tests do not have the purpose of fully replacing full scale ones, but the savings in costs and time that they can provide could be used for mass testing, and this can already show their utility and relevance (GARDINALLI, 2005).

Judging the brake efficience of a vehicle as a whole involves a lot of factors, a small scale test will not provide results that could be used directly to address the quality of a car break system but it is possible to focus the results in the performance of individual componentes of the system such as pads, disks and calipers (HALDERMAN; MITCHELL, 2016), and evaluating the performance of this components is a good start for judge the brake capacity of a brake system.

Braking tests have been carried out for years and have been regulated for some time. A international standard for brake testing has been the regulation *SAE J2522* (SAE, 2016), it gives a the description of how break tests should be conducted for evaluating low weight passengers cars.

1.1 The need for performing brake tests

The brake system is a critical part of an automobile, thanks to this system it is possible to use the latter under safe conditions both in urban and rural areas. There are some ideal requirements that a brake system should be able to attend (KAWAGUCHI, 2005) :

- Reduce the speed of a moving vehicle, increasing the deceleration of the same.
- Stop the vehicle completely.
- Maintain the vehicle speed, preventing unwanted acceleration in downhill paths.
- Keep the vehicle motionless while it is parked.

It is important to emphasize that this conditions are ideal, considering that in extremely hazardous or stressful situations the system might not operate properly and will not attend thoose previous requirementes. Considering the importance of brake system the same need to have minimal breaking capacity so vehicles can be decelerated with greater efficience.

In contrast, more effective brake systems means more cost to manufactures and consenquently to customers. Theoretically this would meant that manufactures need to choose a trade-off between quality and cost. However, the point in which this trade-off is setted is determined by governament regulations. Moreover if there was no general regulations each car manufecturer would have a standard that they judge is sufficient. In Brazil the governament partitions that define this regulations are the *National Traffic Council* and the *National Institute of Meteorology, Quality and Technology*, most of those regulations are based in the european regulation ECE-13/05 (INMETRO, 2013) .

Considering the importance of regulatory standards, the need for brake tests becomes even more evident as it is mandatory to ensure that brake-systems will attend to regulations requirementes. Only with extensive testing it is possible to ensure that a particular system will attend to all standards regarding it's category of operation.

Making all theese considerations, a *Break-System-Testbench* may be considered a useful device for the automotive industry. Considering that it would be able to simulate a close enough replica of real evironments and situations that a brake system is submitted, this testbench could allow car manufactures and break system parts manufactures to avoid expenses in tests as they would be able to test different parts of the system in a assisted and controlled evironment.

1.2 Purpose of the project

The purpose of this work is too develop, implement and test a microcontrolled electronic instrument system for monitoring and controlling a small scale brake-testbench based on the information from the internationl regulation *SAE J2522* (SAE, 2016). The system will comprehend both software and hardware layers and should be able to perform brake tests and acquire physical data through sensors in order to judge brake systems components level of performance.

1.3 Text Structure

The rest of this paper was divided on chapters briefly explained bellow.

Chapter 2, Literature Review: This chapter will explore somo concepts and aspects of engineering and of brake tests that are considered fundamental to following parts of this paper.

Chapter 3, Methodology: This is the where the strategy for developing this paper and the engineering solutions it proposes are dicussed.

Chapter 4, Problem Analysis and Project Requirements: On this chapter the problem this project tries to solve will be defined in a specific way and the project requirements, both from hardware and software will be enumerated. Also, based on this requirements the parameters that the final solution will have to monitor in order to meet thoose requirements will be listed.

Chapter 5, Hardware Project: This chapter provides a detailed explanation of each of the hardware solutions that were either developed, integrated or implemented on this project.

Chapter 6, Software Project: This chapter is basically splitted in two parts, one for explaining the code from the bottom layer of the solution (low level hardware) and one for explaining the code from the upper layer (high level hardware).

2 Literature Review

2.1 Instrumentation Engineering

Instrumentation engineering has existed for long but only recently it has become a independent field of engineering. The instrumentation engineer has a wide variety of work, designing, developing, installing, managing equipments that are used to monitor and control machinery (SHREE, 2016);

Instrumentation engineering may be defined as the branch of engineering that focus on the principle and operation of measuring and control instruments (WEBSTER; EREN, 2014). This kind of engineer may be responsible for integrating the sensors with signal condition circuits and data acquisition systems, transmitters, displays or control systems. Sometimes the instrumentation engineer is the person acquainted to estipulate the hardware/software trade-offs, because this engineer has the proper knowledge to decide which solutions are more feasible and economically viable either using hardware or software solutions (MANDELL, 1972).

“Instrumentation and control engineers work with the industries with the goal of improving productivity, optimisation, stability, reliability, safety and continuity. These engineers design, develop, and maintain and manage the instruments and the instrumentation systems. Instrumentation engineer is the person who takes call on what kinds of instruments are needed for ensuring efficiency and quality of the end product”(YOU, 2012).

2.2 The *SAE J2522* regulation

SAE International was founded in 1905 and the acronym SAE stands for Society of Automotive Engineers. Nowadays their emphasis is on transports industries, such as automotive, aerospace and commecial vehicles. One of their main activity is providing parameters and regulations of quality and safety standards for the industry. One great example of their operation is the SAE has long provided standards for horsepower rating.

More related to this project is the *SAE J2522*, entitled *Dynamometer Global Brake Effectiveness*, at the beggining it already states the it’s utility with the following:

“The SAE Brake Dynamometer Test Code Standards Committee considers this standar useful in supporting the technological efforts intended to improve motor vehicle braking systems overall performance and safety”

(SAE, 2003). This regulation was developed to be used in conjecture with other test standards in other to address the friction of a certain material to check it's adequacy for a certain application. It is important to state that this paper is based on the *SAE J2522*, it is not a faithful application of the standard though. This paper is more concerned about the settings of the tests mentioned on the regulation rather than the formulas and criteria for a materials engineering analysis.

All the tests mentioned on the regulation can generalised on repetitive cycles of accelerating the rotor to a specified speed and appling brake force (may vary along the test) until the rotor reaches a lower limit of speed. On the regulation, sometimes the desacceleration ratio is also defined but not always. Initial temperature is also defined, some tests can only be perfomed if the brake parts are under a certain temperature.

2.3 Working principles of disk brake systems

This section will give a short explanation of how disk breaks works as the vast majority of cars and motorcycles nowadays are equiped with this technology instead of the outdated drum scheme.

In general terms we can make an analogy of how disk brake works with how bicycles brakes works. In a bicycle the brake calipers squeeze the wheels in order to promove deceleration to the wheel and reduce the bike speed. In disk breaks the calipers apply pressure to the rotor *disk*, the rotor is directly connected to the wheel spinning at the same speed, this way the system decelerates the rotor and the wheel trying to reduce the vehicle speed. In car disk breaks there is a component called pad, as seen on Figure 1 pads are located between the calipers and the rotor. Pads have the functionality to reduce the wear generated by friction in the rotor. In normal conditions during proper maintenance calipers are hardly-ever replaced, pads are replaced every once in a while and disks are replaced also every once in a while but less frequently than pads.

2.4 Electronic Background

At this section some electronic components and transducers are going to be revised in order to make paper more acknowledgeable.

2.4.1 Crankshaft Position Sensor

A Crankshaft Position Sensor is shown in Figure 2.

This sensor is widely used in the automotive industry to determine the speed (RPM) of cranks and gears in the engine. There are several types of CKP sensors, the

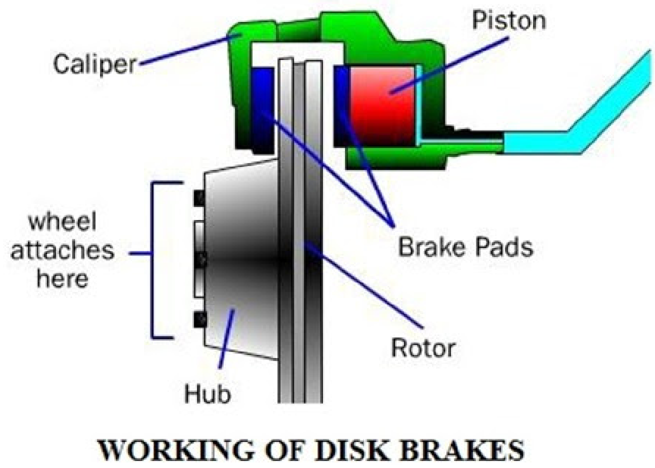

Figura 1 – Schematic for disk brake systems (NICE, 2017)

Figura 2 – *Crankshaft Position Sensor* (REMAN, 2016)

most common are the variable reluctance type because they have low cost and good accuracy (SCHROEDER, 2002).

Variable reluctance sensors, commonly known as magnetic sensors, are passive sensors, that is, they do not require power for their operation. As the gear in question rotates each tooth of the gear aligns with the sensor, a magnetic flux in the sensor coil changes as the air gap between the sensor and the gear changes. This change in the magnetic field generates induces a voltage pulse at the sensor output. This type of sensors have an analog voltage output where amplitude and frequency vary proportionally to the speed of rotation of a gear. With this type of sensor it is possible to extract data of linear velocity, angular velocity and angular position. However, only the angular velocity data (frequency) is important for this project.

2.4.2 Thermocouple

Since the 19^th century it is known that the junction between two different metals submitted to a heat flow generates a electromotive force. A thermocouple is a device

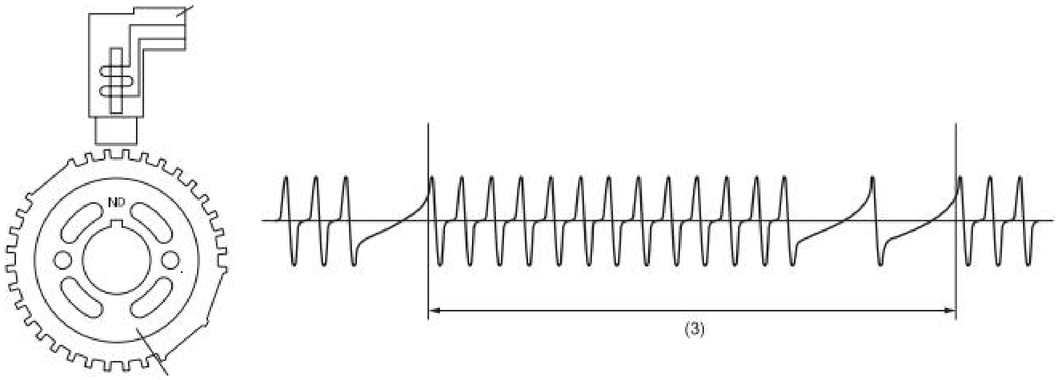

Figura 3 – Magnetic Sensor Signal (DESCONHECIDO, 2016a)

that has this junction of two different metals and has a known voltage generated output proportional to the heat tranfer on the junction. In theory any combination of two different metals could be used, but there are normalized combinations which produces more stable and predictable voltage outputs. (POLLOCK, 1991) This relation between heat transfer and voltage is known not to be linear as Figure 4 shows (E,J,K,T,R,S and B are designators for normalized thermocouples junction types).

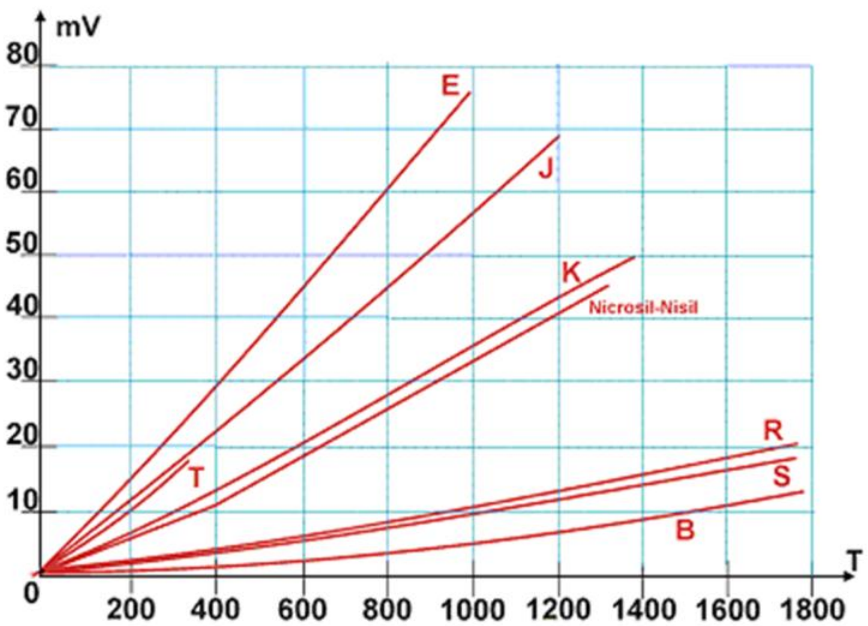

Figura 4 – Thermocouple characteristic voltage output (UNKWNON, 2016)

Thermocouple actually have two junctions, a hot junction (the one that is submitted to heat transfers) and a cold junction (also called reference junction). What the thermocouple really measures is the difference between the temperature of this two junctions, this means that in a hypothetical situation which the hot junction is submmited to a 100°C and the cold junction is submitted to a environmental temperature of 25°C, after thermal equilibrium is reached the thermocouple voltage will be proportional to a temperature of 75°C. Hence the thermocouple will only produce a "real"output voltage when the cold junction is submitted to a 0°C (in some calibrations procedures the cold junction is actually submitted to 0°C) (KINZIE; RUBIN, 1973).

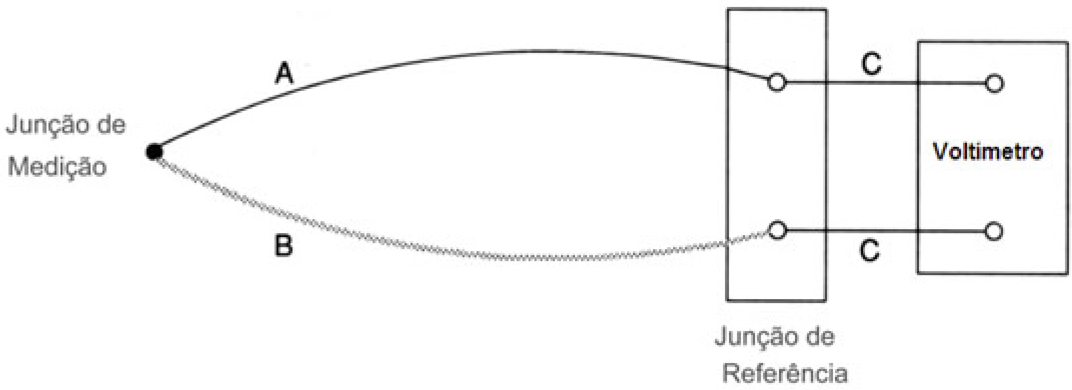

Figura 5 – Thermocouple Measurement (ECIL, 2016)

There is a big variety of thermocouples available, table 1 shows the most common thermocouples and there temperature range.

Table 1 – Thermocouples and their operation ranges

Thermocouple Type	***Range of Operation (°C)***
J	0 a 750
K	-200 a 1250
E	-200 a 900
T	-250 a 350

2.4.3 Load Cell

The load cell is a transducer formed by strain gauges. Thoose are devices which their electrical resistance varies proportionally to their distension. Distension is a quantification of the deformation of a body, it can also be defined as a fractional change of the body of a body. Distension may be negative (compression) or positive (traction).

Generally, the length variation in a strain gauge is very small and this makes them very susceptible to measurement errors. As a result, the use of a Wheatstone bridge is very common, it is formed by four resistive arms and an excitation voltage applied to the bridge (WINDOW; HOLISTER et al., 1982).

The voltage output V_O can be obtained from the Equation 2.1 above:

$$V_O = \frac{R_3}{R_3 + R_4} - \frac{R_2}{R_1 + R_2} \tag{2.1}$$

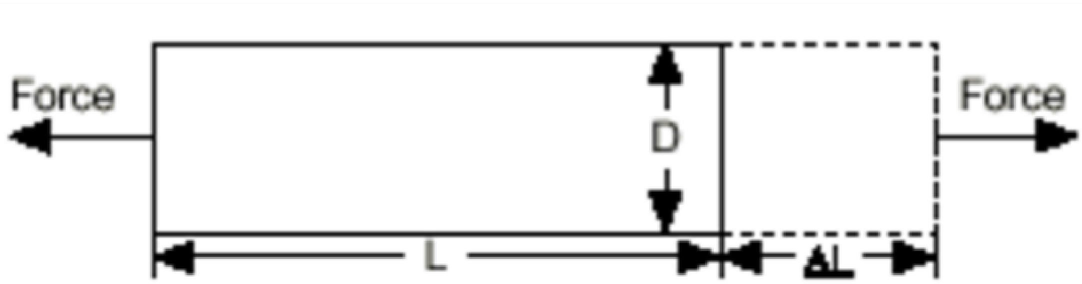

Figura 6 – Distension (INSTRUMENTS, 2016a)

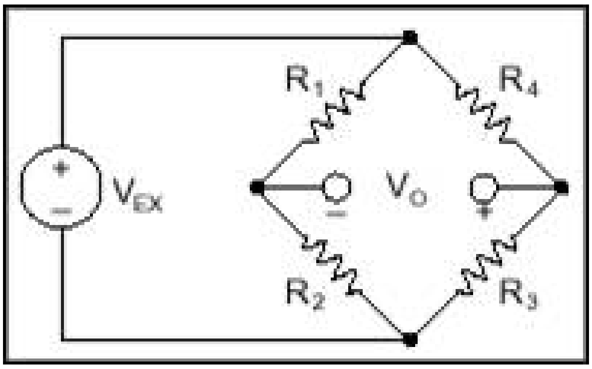

Figura 7 – Wheatstone bridge (INSTRUMENTS, 2016b)

2.4.4 Accelerometer

A body is said to vibrate when it describes an oscillatory movement around a reference point (FERNANDES, 2000). For the measurement of vibration in machines it is more common the measurement of the acceleration as a function of g ($9.8m/s^2$). The same is measured as a function of g as a function of Einstein's Principle of Equivalence, where the acceleration of a reference data is not distinguishable from the gravitational action on it (JR, 1968).

Accelerometers are sensors that measure acceleration itself, that is, the acceleration that the sensor itself is subjected to. Accelerometers are widely used in the automotive industry, initially only in the Air Bag system and currently even for vehicle stability control.

Currently the most common accelerometers are those based on the piezoelectric effect, this effect discreves the variation of electrostatic force or electric voltage in a material when subjected to a force.

By measuring this variation of electrostatic force or electrical voltage it is possible to determine the acceleration that the sensor has undergone. In Figure 8 we can observe that there is a mass in the piezoelectric material, so when the sensor is submitted to some movement, based on the principle of inertia the mass will exert a force of traction or compression which will generate a voltage variation at the sensor output (PATRICK,

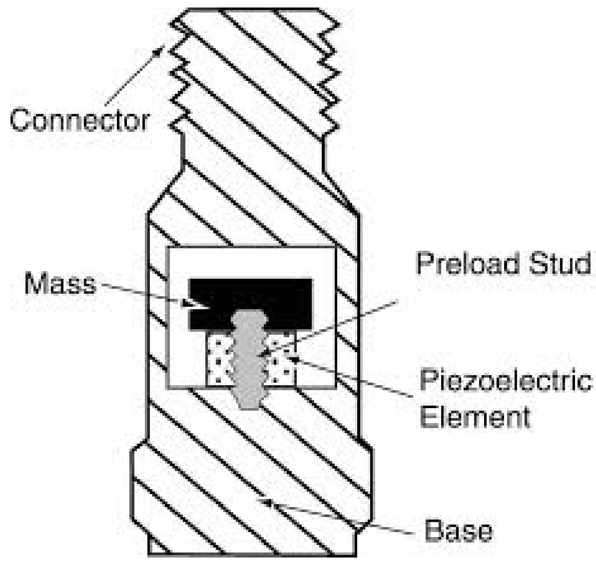

Figura 8 – Piezo Accelerometer (UK, 2016)

2007).

2.4.5 Instrumentation Amplifier

2.4.5.1 The Operational Amplifier

A Operational Amplifier can be defined as a voltage amplifier with a differential input and a single-ended output. Operational Amplifiers are usually refered just as *OpAmps*. Thoose devices are largely used in eletronic circuits, theoretically they have infinite input impedance and infinite gain, this means that OpAmps do not drain current from the signals they are amplifying and they can amplify this signals with any gain (MANCINI, 2003). Figure 9 shows the schematic symbol of the OpAmp.

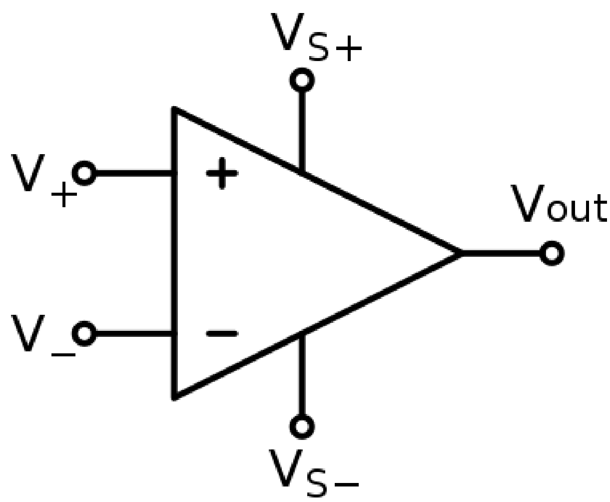

Figura 9 – Operational Amplifier (OMEGATRON, 2007)

V_+ and V_- are the OpAmp inputs, V_{S+} and V_{S-} are the power supply inputs. The voltage output V_{out} is limited to the voltage values given by the power supply inputs. The gain of a operation amplifier can vary according to it's configuration, only the configuration relevant to this paper will be explained.

2.4.5.2 The Closed-loop amplifier

This may be the most common configuration for the operational amplifier.

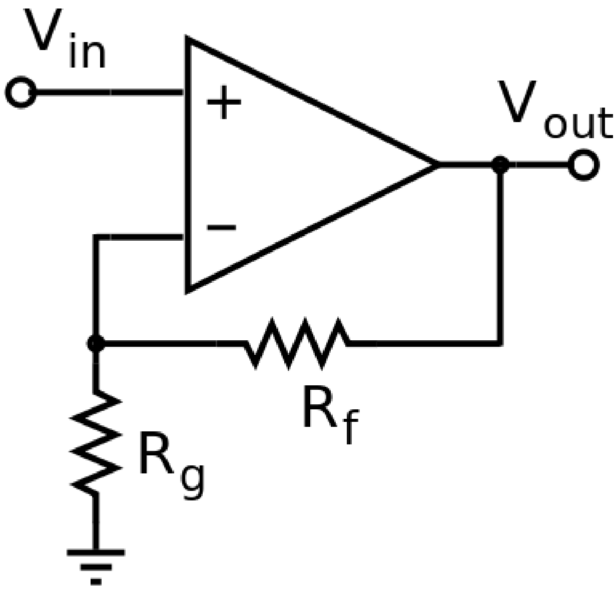

Figura 10 – Operational Amplifier (SALURI, 2009)

The output voltage of this amplifier is given by Equation **??** (DORF; SVOBODA, 2014a).

$$Vout = \left(1 + \frac{R_f}{R_g}\right) \cdot V_{in} \tag{2.2}$$

The disadvantage of this OpAmp configuration is that only gains greater than one are achievable, in electronic instrumentation this is not a common issue because in this field of electronic engineering amplification is usually done to increase the resolution of signals, not to reduce it.

2.4.6 The Instrumentation Amplifier

In general, sensors and tranducers have very low voltage output levels (specially passive transducers), and therefore an amplification is fundamental. The most commonly used amplifier circuit in instrumentation engineering is the common joint differential amplifier more commonly refered as *Instrumentation Amplifier* (Figure 11), which is very stable and significantly reduces the output signal noise (WAIT; HUELSMAN; KORN, 1975).

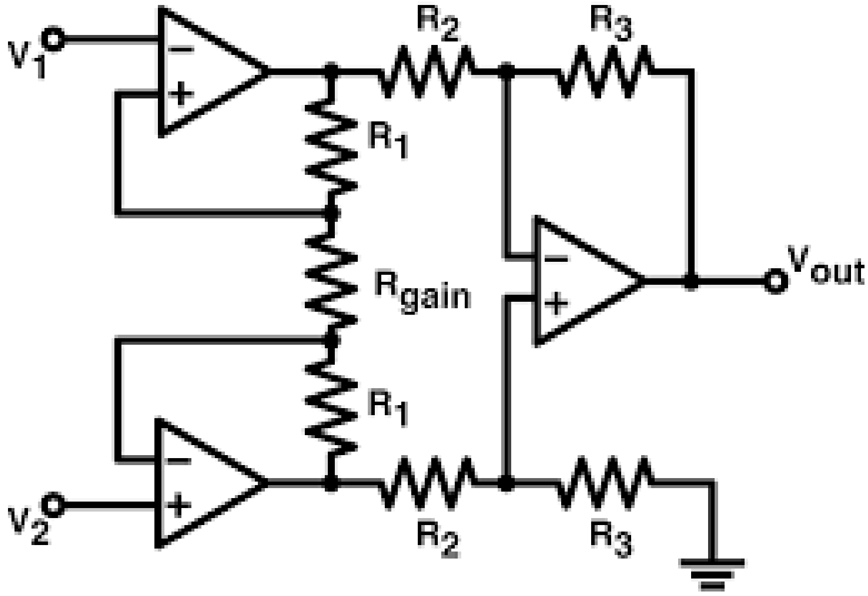

Figura 11 – Instrumentation Amplifier (DESCONHECIDO, 2016b)

The instrumentation amplifier has two stages, the first stage consists in amplifying both inputs of a sensor, with the gain of this amplification stage controlled by R_{gain} in Figure 11. The second stage consists in taking the difference of the two input signals. If the differentiation happens before the amplification, noise may be so big in the input signals that some signal information might be lost. In the instrumentation amplifier noise and signal is amplified on the first stage, considering that the noise is similar in both inputs the differential stage will take out the noise and only output the difference between both inputs. One advantage of this amplifier is that it has high input impedances, that means it will not drain significant current from the signal, i.e., it will not interfere with the measure (THOMSEN et al., 2003). Another advantage is that the gain of this amplifier can be adjusted with just one resistor (METTINGVANRIJN; PEPER; GRIMBERGEN, 1994).

The gain of the instrumentation amplifier is given by the following 2.4.6 (COUNTS; KITCHEN, 2006).

$$Vout = (V_2 - V_1) \cdot \left(1 + \frac{2 \cdot R}{R_{gain}}\right) \tag{2.3}$$

Something interesting to notice is that if we take out the R_{gain} (open load), the gain of the amplifier is equal to one. Besides this advantageous behavor of the instrumentation amplifier, it is quite hard to make it work with seven resistors and three operation amplifiers because of components imprecision. Hence, it is more practical to work with ICs that ensure the symmetry of between those components. As an example, there is the Texas Instruments INA118 (INSTRUMENTS, 2000b), which is one of many encapsulated solutions for the instrumentation amplifier, the schematic of this component is shown in Figure 12.

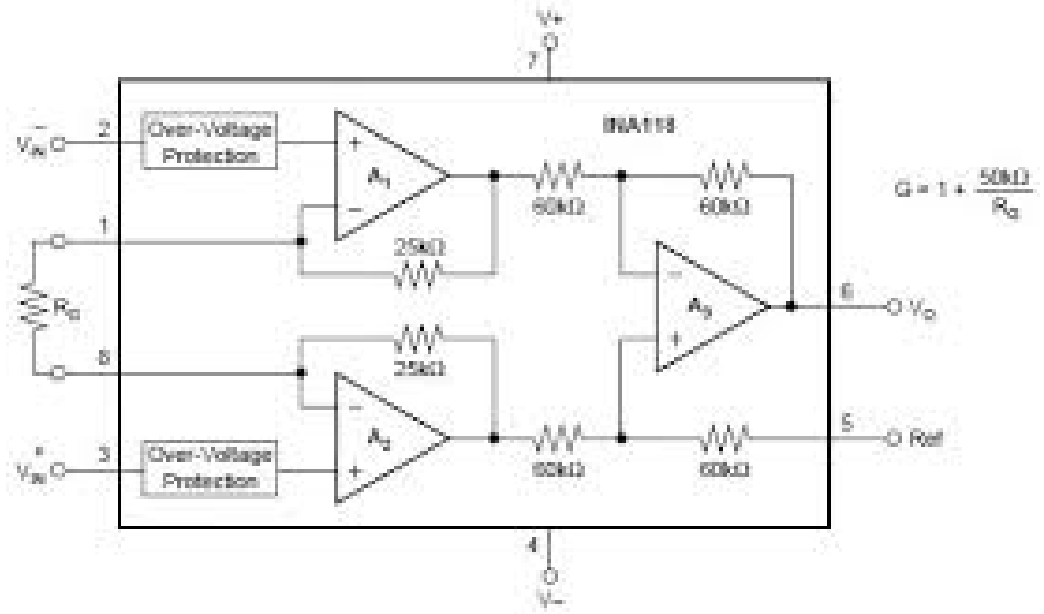

Figura 12 – INA 118 (INSTRUMENTS, 2000a)

2.4.7 The Relay

A relay is a device that acts as an electromechanical switch, it consists of three basic parts: a coil, a set of contacts and a reset spring as shown in Figure 13. When an electric current flows through the coil, this creates a magnetic flux that changes the state of the set of contacts thus changing the position of the switch. When the coil is de-energized the reset spring returns the key to its natural state. The relays are used for various applications in the automotive industry, because a relay allows two circuits to interact without there being an electric current transfer between them, in this way smaller power circuits can control higher current circuits and vice versa (KELLER, 1962) .

2.4.8 Microcontroller

A microcontroller is a compact computer on a single integrated circuit chip, in most cases a microcontroller (also refered by the acronym MCU) includes a processor,

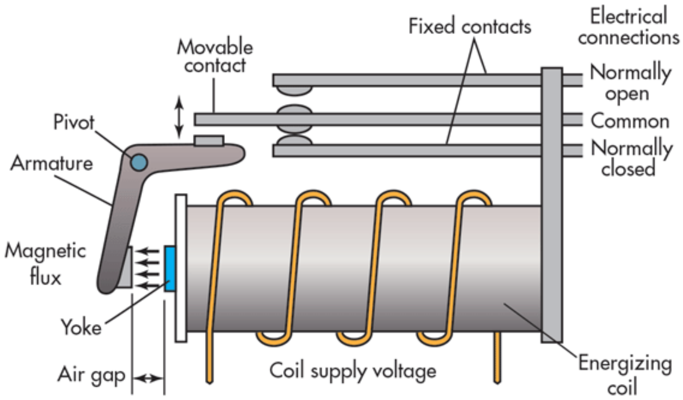

Figura 13 – Schematic Relay (TESCHLER, 2016)

volatile and non-volatile memory, input/output ports and other peripherals. The great thing about the microcontrollers is their low cost, many small appliances that does not require a powerful hardware are only economically viable because of those devices. The components a microcontroller has may vary, it is a responsability of the project designer to decide the microcontroller that has the best fit (technically and economically) for the project.

Microcontrollers differ from microprocessors only in one thing, MCUs can be used standalone while microprocessors need other peripherals to be used. By reducing the size and cost compared to a design that uses a separate microprocessor, memory, and input/output devices, microcontrollers make it economical to digitally control even more devices and processes. “A microprocessor can be considered the heart of a computer system, whereas a microcontroller can be considered the heart of an embedded system”(ROUSE, 2012).

A great thing about microcontrollers is that they must provide provide real-time response to events, so for instrumentation they are crucial. With them it is possible to acquire signals with good sampling rates without loss of relevant information. It is common in electronic instrumentation to use MCUs to handle the events that have real-time constains and use more sophisticated hardware solutions to manage and process the acquired data later (BARTZ; ZHAKSILIKOV; OGAMI, 2004).

2.4.9 Pulse Width Modulation

Pulse Width Modulation (PWM), is a way of modulation for encoding information on a pulse train signal. There are many ways of encoding and extracting this message in and out of the PWM signal and this type of modulation can be used for a wide varriety of applications such as controlling the charge delivered to a load and transmitting information (STANDARD, 1996). PWM signals have a fixed high and a fixed low voltage level, there are two parameters that can be varried on a PWM signal: oscilation frequency and duty cycle. Figure 14 shows how a the duty cycle affects a PWM signal.

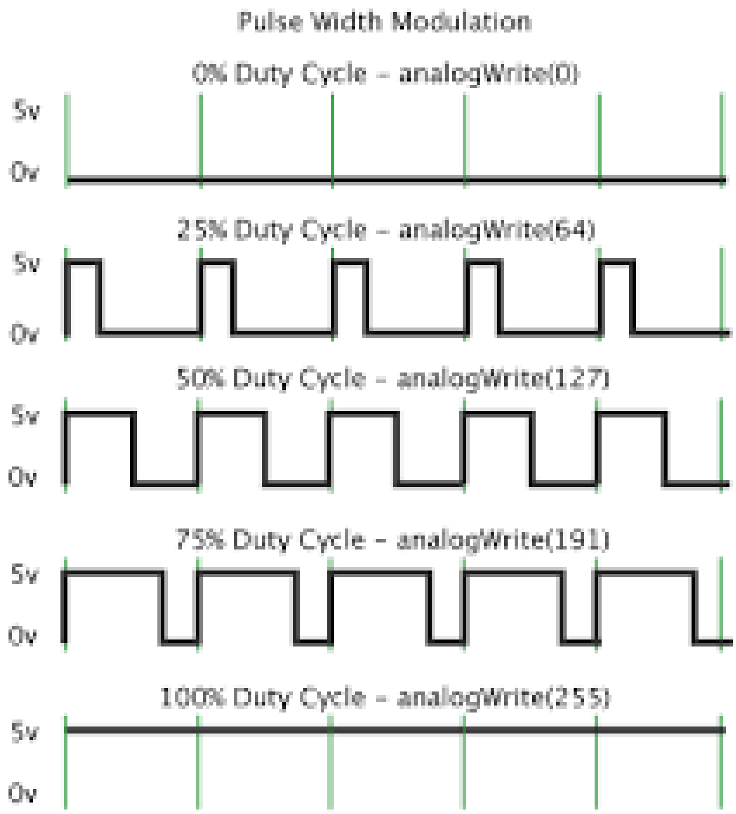

Figura 14 – Duty Cycle Examples (RZTRONICS, 2016)

Duty cycle can be defined mathematically by the Equation 2.4 (JAMES, 2001), where $D_{\%}$ is the duty cycle in percentage, PW is the pulse width (pulse active time) and T is the wave period.

$$D_{(\%)} = \frac{PW}{T} \tag{2.4}$$

One useful way of using a PWM duty cycle variation is by enconding a analog voltage level proportional into it's percentage (HOLMES; LIPO, 2003), meaning that 100% duty cycle would represent maximum voltage amplitude and 0% the minimum voltage. This means it is possible to extract a analog voltage level by taking a PWM average level (ALTER, 2008), this is a practical way for designing digital to analog converters.

2.4.10 Serial Communication

2.4.10.1 Definition

2.4.10.2 USB

2.4.10.3 UART

3 Methodology

In other to achieve the goals of this project the endeavours were divided into three

3.1 Lieterature Review

This stage can be considered the most important of the whole project because it layers the foundations for development of all that follows. This stage comprehended the knowledge needed in all further stages and steps of the project, even on the further stages of development it was necessary to review some of the information acquired on this part in other to achieve best results. On the Literature Review stage, concepts, components and other necessary information to make the foundations for the project were adressed. For instance it will be on this stage that the brake tests parameters and requirements will be analysed in order to choose the proper solutions for this project.

3.2 Problem Description

This particular stage consisted on the depuration of the problem in question, leading to a study of the requirements that were necessary to ensure in other to develop and execute the project.

3.3 Project Conception

After a deep problem analysis it was possible to adress a more detailed solution description, in this stage the general solution was splitted in many smaller ones that were defined according to the requirements of the previous stage. All this solutions were focused in functionality, this is a project of electronic instrumentation, so the goal was not to develop electrical/electronic solutions from the beggining, it was evaluating the requirements and finding a group of components/solutions that combined in a particular and unique way could lead to this project achieving it's goals.

3.4 Case Study

After the particular and smaller solutions are developed, tested and considered functional, the general solution of this project will be tested as a whole thing. This being doing a brake test that is capable of proving the functionality and usability of the developed technology.

4 Problem Analysis and Project Requirements

4.1 Problem Analysis

As mentioned in Section 1.2 this project aims on developing a functional brake test bench. Based on the *SAE J2522* (SAE, 2016) and considering some instrumentation engineering concepts the project solution can be divided in the structure showed in Figure 15.

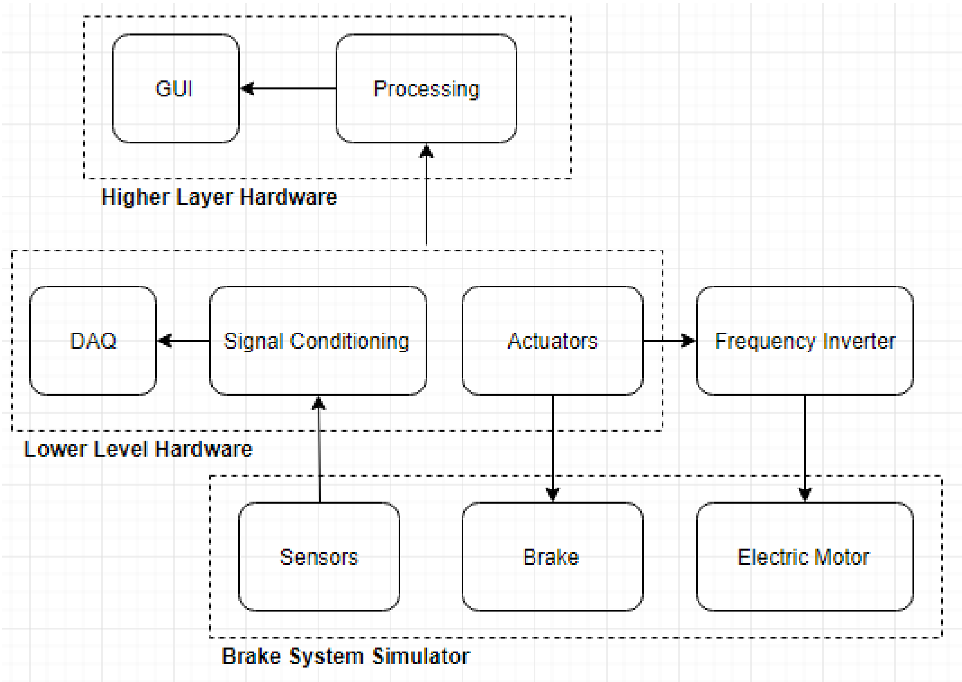

Figura 15 – Project Problem Depuration (GUIMARAES, 2017c)

The explanation of the structure of Figure 15 will be explained in Sections 4.1.1 to 4.1.4.

4.1.1 Brake System Simulator

The *Brake System Simulator* block as the name says comprehends the hardware responsible for simulating the environment of a brake system, the two basic components are the *Brake* component itself (in this case being a disc brake system) and a *Electric Motor* to accelerate the rotor in order to simulate the speed a vehicle wheel might be submitted. A *Sensors* block was also added, without acquiring a physical/mechanical quantities such as temperature and pressure, a brake test would be useless because no possible technical analysis could be done afterwards. The *Sensors* block was placed inside the *Brake System Simulator* block because the sensors and transducers will be placed arround the components of this major block.

4.1.2 Lower Layer Hardware

This layer of hardware will make the translation from physical/mechanical quantities to computer data, *i.e.*, converting physical/mechanical quantities to voltage and than to bytes of information and also on the opposite way (bytes to voltage and voltage to physical/mechanical quantities). *Sensors* signals are not always ready to read, as mentioned in Section 2.1, Instrumentation Engineering also involves doing *Signal Conditioning* to adapt sensor signals. The *DAQ* block was inserted in order to demonstrate that there is the need for a solution to capture the sensors signals. *Actuators* block are responsible to adapt the commands from upper layers to control the hardware. The *Frequency Inverter* is already a more specific detail of the solution, but it was included here because most electric motors work with triphasic power and this device is fundamental to control them.

4.1.3 Higher Layer Hardware

This layer of hardware although represented in a quite simple way in Figure 15 will probably involve the most dense code. This is because this layer needs to do all the heavy data processing, *i.e.*, converting and dealing with the information that flows through all the structure. The *GUI* block is the one responsible for acquiring and displaying computer information in a human-friendly format.

4.1.4 Solution Overview

Table 2 shows the basic functon of each block on Figure 15.

Table 2 – Blocks functionality

Block	**Function**
Sensors	Convert physical quantities to electrical signals
Signal Conditioning	Adapt sensors electrical signals to best suit DAQ
DAQ	Converts electrical signals to computes bytes
Actuators	Convert voltage levels to physical/mechanical quantities
Frequency Inverter	Controls a triphasic motor speed
Processing	Control and process data flow
GUI	Displays/acquire information in a human-friendly format

4.2 Monitored parameters

As metioned before this paper will be based in the *SAE J2522* regulations, this regulation says that to evaluate the efficiency of a brake system it is mandatory to monitor temperature on the brake pads, the pressure applied on the disk and the speed of the rotor throughout all the process. Monitoring the vibration is not mandatory but has some advantages.

- *Temperature of brake pads:* During all test it is mandatory to have full knowledge of the temperature of the break pads, firstly because of security reasons (there is upper limit for temperatura in any system) and also because of the wear of parts that is related to temperature.
- *Pressure applied on the disks:* Knowing the magnitude of this force means being able to relate the pressure applied and the deceleration, knowing how the pressure applied increases the temperature of the pads and evaluate how this promotes wear of the parts.
- *Rotation speed:* Without knowing how the speed of the rotor varies over time it would be impossible to determine the acceleration and deceleration rates among many other issues.
- *Vibration:* As mentioned before this is not mandatory but rather interesting, measuring vibration makes it possible to determine how the extensive use can wear out the parts and reduce stiffness among other properties. Also it is natural that the system will vibrate during braking, minimal vibration or too much vibration can indicate a fault that on the future could damage the system.

4.3 Functional Requirements of the Testbench

According to the specification of the *SAE J2522* and according to parameters considered to be important, some requirements for the testbench were defined.

1. Measure a braking pressure up to 16 MPa.
2. Apply a braking pressure of at least 300 kPa.
3. Measure temperatures up to 600 °C
4. Measure temperatures with a minimal resolution of 7.5 °C.
5. Accelerate the rotor to a speed up to 200 kph.
6. System most have a sampling period of 50ms.

7. The system hardware most be able to operate under temperatures up to 40°C.
8. System must two acquisition channels for temperature.
9. System must have at least one channel for braking pressure acquisition.
10. System must have a channel for vibration acquisition.
11. System must have at least two digital outputs to control relays.
12. System must have a channel for acquiring speed.
13. The system must work with real time acquisition.

4.4 Software Requirements

1. System must have a sampling rate of 50 ms.
2. System must be able to monitor six analog channels at once.
3. System must be able to control the digital outputs and one analog output during acquisition without loosing the real time constrain.
4. The data acquired does not need to be shown to user in real time.
5. The software layer must be able to record the data of the test.
6. The software highest layer must have a friendly GUI, advanced electronic and simple programmable knowledge cannot be a requirement to operate the software.
7. Calibration of the sensors data must be easy to modify on the software.
8. Software must be multiplatform.

5 Hardware Project

Based on the matters analysed on the previous sections of this paper a hardware architecture was defined and it displayed on the following Figure 16.

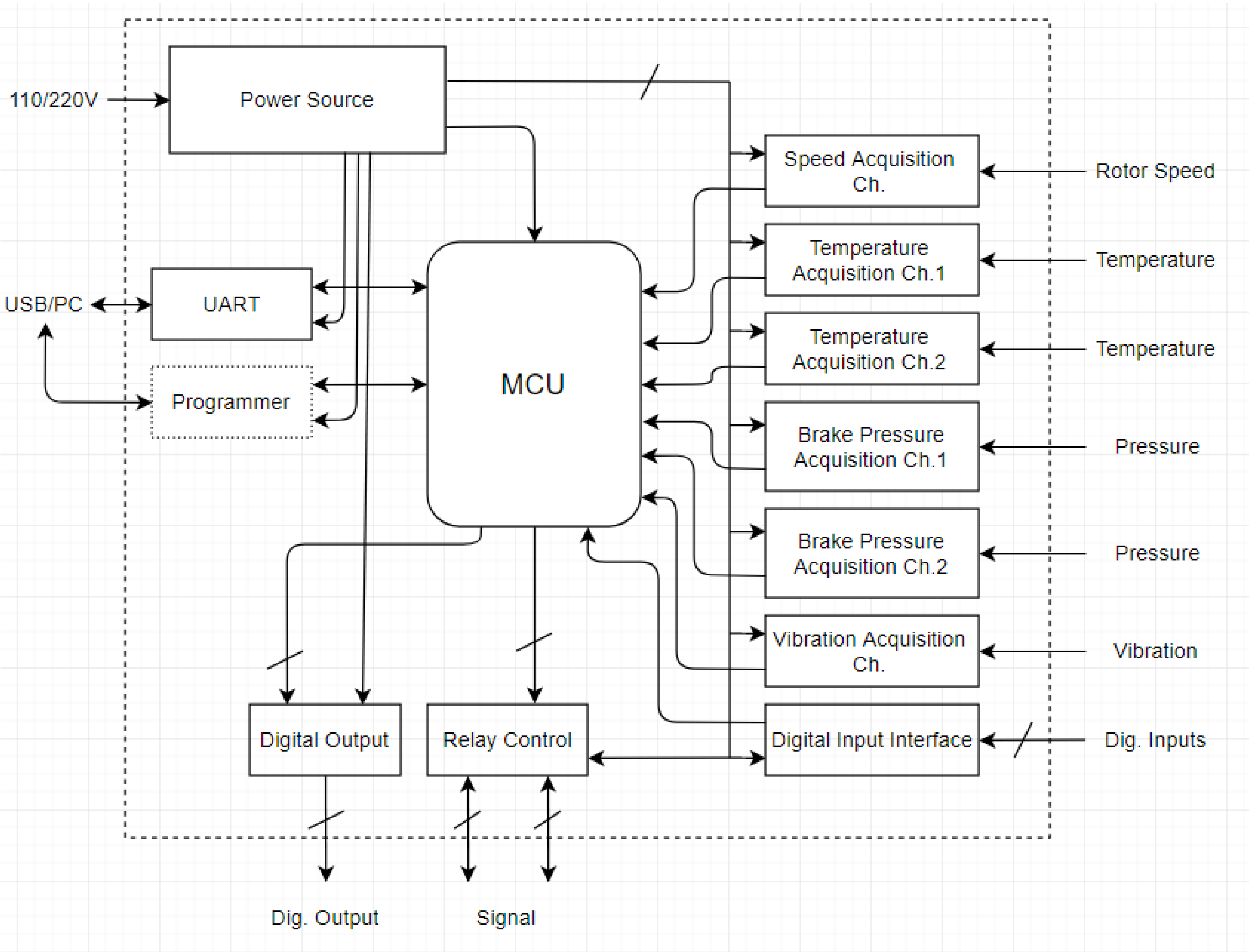

Figura 16 – Hardware Project Architecture (GUIMARAES, 2017a)

5.1 Temperature Acquisition Channel

5.1.1 Thermocouple Type and Signal

For this project it was defined that thermocouples of type K (formed by the junction of two metal leagues: Alumel and Cromel) would be used in this project. This is because this specific type of thermocouple has a wide range of operation (-200°C - 1200 °C), so according to the requirements they are never too close from the boundary values, a thermocouple of type T or even a type J would not be suitable. Other appealing factor is that this type of thermocouple is quite common so getting eventual replacements would be easier, in comparisson with type E thermocouples.

5.1.2 Thermocouple Signal Conditioning

As mentioned in sub-section 2.4.2, besides amplification and linearization, the thermocouple signal also needs it's cold junction temperature difference compensation. There is an integrated solution from *Analog Device* called AD8495, this IC functional diagram is displayed on Figure 17.

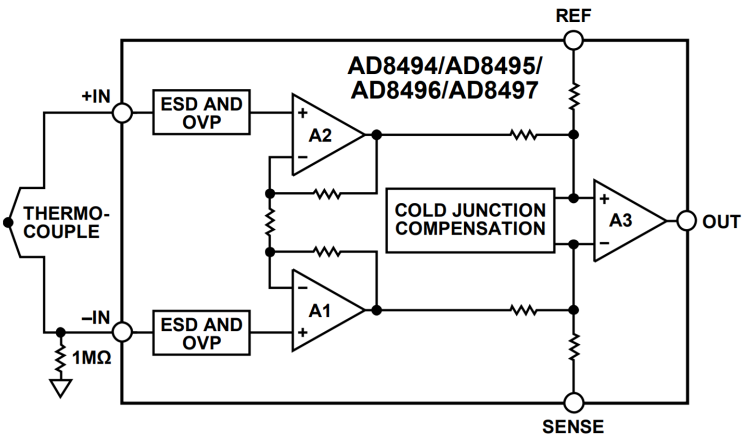

Figura 17 – AD8495 Functional Block Diagram (DEVICES, 2011)

This IC produces a linearized output with a fixed gain of 5mv°C, it is a quite practical solution as it can be powered with single-supply voltage source and it's output saturates to the power supply voltage if the thermocouple is disconnected (ANALOG DEVICES, 2010).

5.1.3 Input Protection and Filtering

Although this IC already has overvoltage and ESD protection, thermocouples tips can pick a load of unwanted noise and transients. Hence, additional protection and external filtering is also recommended by (DUFF; TOWEY, 2010). First thing to do is to add current-limint series resistors, the drawback is doing that is that resistors in the circuit net increases the overall noise. This type of noise is called Johnson-Nyquist Thermal Noise or more commonly just by Johnson Noise, thermal agitation of electrons in a resistor gives rise to random fluctuations in the voltage across its terminals (ROMERO,). Moreover, it can be calculated using the following Equation 5.1 where K is the Boltzamann's constant $1.38 \cdot 10^{-23}$, R is the resistance in ohms (Ω) and T the temperature in kelvin (300K at room temperature) (BRYANT et al., 2000).

$$Noise(nv\sqrt{Hz}) = \sqrt{4 \cdot K \cdot R \cdot T \cdot 10^9} \tag{5.1}$$

Because the protection circuit includes two equal resistors, whose noise is uncorrelated, that is, the two noise sources are independent of each other—the above result must be multiplied by the square root of 2 (the root sum square of the two noise voltages) and it is considered as a general rule design to tolerate additional Johnson Noise from 10 to 30% to the amplifier IC (BRYANT et al., 2000). (DUFF; TOWEY, 2010) suggests using current-limiting resistors of $10k\Omega$, according to the AD8495 datasheet (ANALOG DEVICES, 2010), the choosen amplifier (AD8495) has a voltage noise density of 32nV$\sqrt{Hz}$. Combining this resistors noise with the amplifier noise will produce a overall noise of 36.85nV$\sqrt{Hz}$, which is just 13% above the amplifier's own noise. Additional protection can be achieved using (TVS) to protect the inputs from differential input overvoltage, considering a bidirectional TVS with a 10V breakdown voltage, the device will theoretically limit the differential voltage between 10V and -10V, the AD8495 has overvoltage protection from -25V to 20V when powered with 5V, so this will successfully protect the amplifier inputs.

With the overloads protection done, another important feature to do is to filter unwanted signals in the inputs to avoid them to be amplified later, this is done by filtering Radio Frequency Interference (RFI), signal lines (specially for low level signals) are quite susceptible to RF interference (COUNTS; KITCHEN, 2006). Interference that occurs on both lines are usually reduced by the amplifiers own common-mode rejection filter, but only on a limited bandwidth, also the in-amp rectifier cannot filter differential RF interference. The choosen amplifier (AD8495) has a -3dB bandwidth at 25kHz, (DUFF; TOWEY, 2010) suggests setting a common-mode cutoff filter frequency at 16kHz (in order to guarantee the input signal within the 25kHz bandwidth). The standard circuit for the RFI filter is displayed on Figure 18, resistors R and capacitors C_C are used to filter common-mode interference. Capacitor C_D is connected across the bridge output to reduce any common-mode rejection errors due to the components mismatch, that way filtering any differential interference. C_D is usually choosen to be ten times larger than C_C (ANALOG DEVICES, 2010).

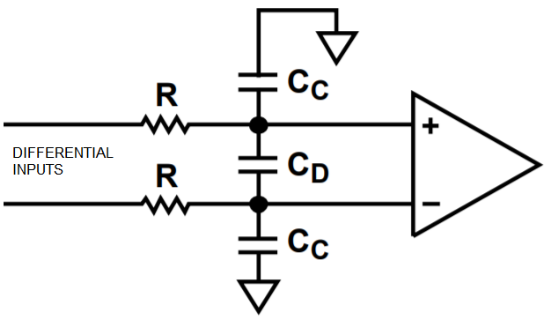

Figura 18 – RFI Circuit (GUIMARAES, 2018a)

The -3dB common-mode bandwidth of this filter from Figure 18 is given by Equation 5.2 (COUNTS; KITCHEN, 2006).

$$BW_{CM} = \frac{1}{2 \cdot \pi \cdot R \cdot C_C} \tag{5.2}$$

The -3dB differential bandwidth of this filter from Figure 18 is given by Equation 5.3 (COUNTS; KITCHEN, 2006).

$$BW_{DIFF} = \frac{1}{2 \cdot \pi \cdot R \cdot (2 \cdot C_C + C_d)} \tag{5.3}$$

Using the values for the current limiting resistors (10kΩ), Equation 5.2 and the suggested cutoff frequency of 16kHz (DUFF; TOWEY, 2010), it is possible to calculate a value of 1nF for C_C. Choosing a C_D value ten times larger than C_c implies on using a C_D value of 10nF, that used on Equation 5.3 will produce a differential interference filter cutoff frequency of 1.3kHz.

5.1.4 Thermocouple Sensor Detection

A important feature of any acquisition system is to detect when a sensor is disconnected from the the acquisition system input (O'MAHONY; GELFAND; MERRICK, 2011), because a signal acquisition circuit without the signal source will generate outputs that are uncorrelated to what the system was designed to measure/sense on the outside world. The AD8495 has a quite useful feature (ANALOG DEVICES, 2010), it offers open thermocouple detection, the inputs of the AD8495 are PNP type transistors, which means that the bias current always flows out of the inputs. This way, the input bias current drives any unconnected output high, which saturates the output to the maximum possible reading, being in this case 1000^{o}C or 5V (considering the fixed 5mv^{o}C gain. In Section 4.3, it was defined that the system must measure temperatures up to 600^{o}C, with the fixed gain of 5mv^o this means an output voltage of 3V. The so called *Thermocouple Sensor Detection* must be able to detect whenever the output exceeds 3V. In order to do that, the circuit displayed in Figure 19 was designed.

U11 is a OPAMP working as a comparator, whenever the thermocouple signal is higher than the *4V5_VREF* the OPAMP output will saturate to the 5V (the supply voltage applied to the OPAMP). The net *4V5_VREF* will be further explained in Section **??**, whereas it is a constant voltage produced on the Power Supplies circuit block. The resistor *R77* is just a pull-down resistor to reference the output to the GND net. The capacitor *C31* is just a decoupling capacitor for the OPAMP power supply. The resistors R73 and R71 should not be required and shall not be soldered on the circuit board, they were added to the circuit just to reserve the space for there footprint on the PCB just

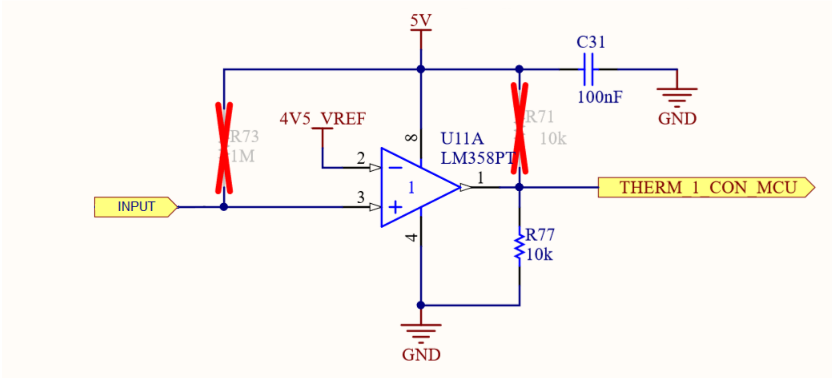

Figura 19 – Overvoltage Detection Circuit **??**

in case for some unexpected reason thoose nets would be neeeded to be shorted to be connected to the 5V power supply.

5.1.5 Complete Circuit

The thermocouple complete circuit is displayed on Figure 20.

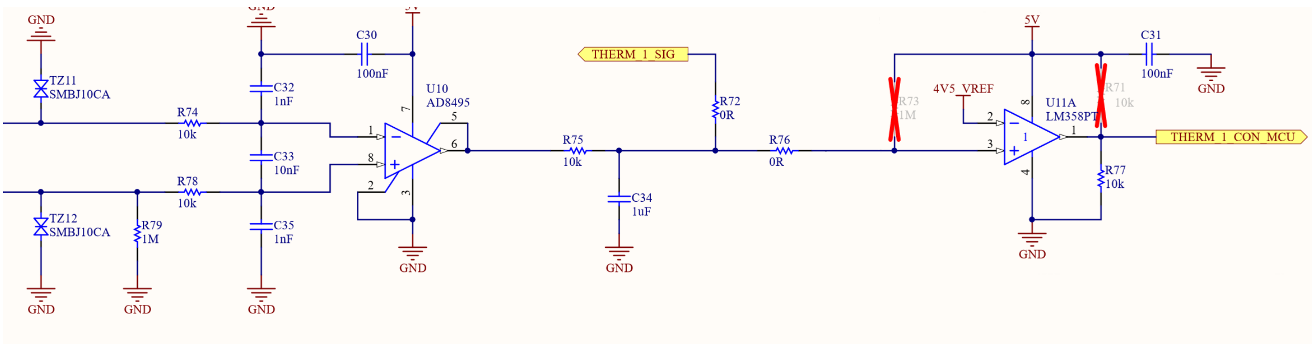

Figura 20 – Thermocouple Complete Circuit (GUIMARAES, 2018b)

As mentioned in Subsection 5.1.2, a TVS was added on each of the thermocouple signal lines, the SMBJ10CA (LITTELFUSE, 2017) was choosen because it has a maximum clamping voltage of 17V/-17V, which will guarantee that the voltage levels will not surpass the 20V/-25V limits of the AD8495. R79 is a resistor that is recomended by the amplifier's IC to enable to sensor detection functionality. The pair composed of R84 and C39 is a LFP with a central frequency of 16Hz, used to filter any further noise including the 50/60Hz noise from AC power lines that the thermocouple wires may catch. R81 and R85 were included in case a individual circuit block test is required, both are 0R resistors (jumpers).

5.2 Speed Reference Output Channel

5.2.1 Speed Control

For the braketests, somethings as important as measuring the speed of the rotor is controlling it, as mentioned in Subsection 4.1.2. The rotor speed can be controlled in two ways:

- First way is the deceleration of the rotor with the aid of the brake system using the brake pads.
- Second way of controlling it by accelerating the rotor with the aid of the electric engine.

The electric engine used is a alternate current three-phase type, it in order to control it's speed a frequency inverter was used. The frequency inverter has many different controlling interfaces that lead to manipulating the three-phase electric system in order to control the engine's rotationary speed.

In this project the frequency inverter used was the *Weg CFW-08* (WEG, 2009), one way of controlling the speed of the rotor using this device is by using it's analog input, it can be configured as a notch to ten volts input that has a linear proportion to the the output frequency that goes to the engine, that way the problem to figure out in this solution is how to implement a analog output from a microcontroller that only has digital outputs.

Figura 21 – Weg CFW-08 Frequency Inverter (WEG, 2017)

5.2.2 Filter characteristics definition

Fortunately the microcontroller has pre-configured PWM *(Pulse Width Modulation)*, as explained in Subsection 2.4.9, a PWM signal can encode a analog voltage value proportional to it‘s duty cycle, and this is usually done with the aid of a low pass filter that will extract this analog voltage from the PWM signal. As said in the previous paragraph the frequency inverter used in this project is the *Weg CFW-08*, and it's analog input has a zero to ten voltage input with eight bits of resolution. We can calculate the minimal voltage difference that will change the output frequency of the device using Voltage, in which ΔV is the minimal voltage difference, V_{max} is the maximum voltage and *"n"* is the number of bits of the input resolution.

$$\Delta V = \frac{V_{max}}{2^n} \tag{5.4}$$

As mentioned in Section **??**, the choosen MCU has a five volts high logic level, this voltage level will need amplification in order to best suit the zero to ten volts input from the frequency inverter. According to (ALTER, 2008), converting a PWM signal to a analog voltage generates a constant voltage ripple. It was decided to amplify this voltage prior to filtering because this way the voltage ripple generated from the filtering stage will not be amplified. Using a OPAMP and two resistors it is possible to convert a five volts amplitude square wave (PWM wave) to a 10V amplitude wave by giving a gain of two to the input signal. Using Equation 2.4.5.2 from Sub-section 2.4.5.2, it is possible to achieve the desired gain of two using both R_f and R_g of 10kΩ as Figure 10 shows how to.

The maximum ripple is the ΔV from Equation 5.4. Equation 5.5 (METIVIER, 2013) gives the necessary $\frac{dB}{decade}$ attenuation to guarantee a PWM converted signal desired ripple.

$$A_{dB} = 20 \cdot log\left(\frac{V_{RIPPLE}}{V_PWM}\right) \tag{5.5}$$

As the V_{PWM} will already be aplified prior to filtering, $V_{PWM} = V_{max}$, this will produce the following Equation 5.6.

$$A_{dB} = -20 \cdot n \cdot log\left(2\right) \tag{5.6}$$

And Equation 5.7 (METIVIER, 2013), is used to calculate the maximum needed cuttoff frequency for the further to be designed LPF (*Low-Pass-Filter*) in order to convert the PWM signal to a analog voltage. This cutoff frequency can not be to much smaller than the one calculated otherwise this will have negative consequences to the output signal (KEIM, 2016). The slope value is the filter slope and for first order filters and second order filters this slope value is equal respectively to 20dB/decade and 40dB/decade (METIVIER, 2013).

$$f_c = f_{PWM} \cdot 10^{-\frac{A_{dB}}{Slope}} \tag{5.7}$$

It is possible to combine all this equations into one single equation to calculate the needed cutoff frequency, is this done in Equation 5.8.

$$\begin{aligned}
f_c &= f_{PWM} \cdot 10^{-\frac{A_{dB}}{Slope}} \\
f_c &= f_{PWM} \cdot 10^{-\frac{-20 \cdot n \cdot log(2)}{Slope}} \\
f_c &= f_{PWM} \cdot 10^{log\left(2^{\frac{20 \cdot n}{Slope}}\right)} \\
& Knowing: \\
x \cdot log\left(A\right) &= log\left(A^X\right) \\
10^{log(A)} &= A \\
& So: \\
f_c &= f_{PWM} \cdot 2^{\frac{20 \cdot n}{Slope}}
\end{aligned} \tag{5.8}$$

As shown in Appendix A.1, the PWM frequency was defined so $f_{PWM} = 62.5kHz$, also $n = 8$ and as according to (METIVIER, 2013), a second order LPF is better for converting a PWM signal to voltage and it has by default $Slope = -40dB/decade$, using Equation 5.8 it is possible to calculate a maximum cutoff frequency of 3906.25Hz.

5.2.3 Sallen-Key Low Pass Active Filter

The Sallen-Key LPF setup is probably one of the best second order filters architectures available (DORF; SVOBODA, 2014b), this setup is displayed on Figure 22.

According to (TEXAS INSTRUMENTS, 1999), this filter setup has a cutoff frequency defined by Equation 5.9, quality factor (Q) defined by Equation 5.10, gain (k) defined by Equation 5.11 and cutoff frequency giver by Equation 5.12.

$$H(s) = \frac{k}{s^2 \cdot (R_1 \cdot R_2 \cdot C_1 \cdot C_2) + s \cdot (R_1 \cdot C_1 + R_2 \cdot C_1 + R_1 \cdot C_2 \cdot (1-k)) + 1} \tag{5.9}$$

$$Q = \frac{\sqrt{R_1 \cdot R_2 \cdot C_1 \cdot C_2}}{R_1 \cdot C_1 + R_2 \cdot C_1 + R_1 \cdot C_2 \cdot (1-k)} \tag{5.10}$$

$$k = 1 + \frac{R_3}{R_4} \tag{5.11}$$

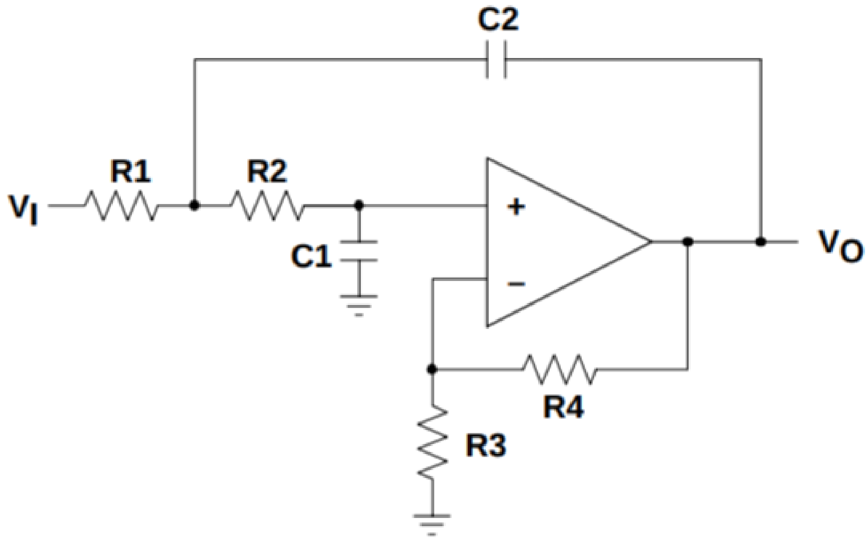

Figura 22 – Sallen-Key Active Low Pass Filter (TEXAS INSTRUMENTS, 1999)

$$f_c = \frac{1}{2 \cdot \pi \sqrt{R_1 \cdot R_2 \cdot C_1 \cdot C_2}} \tag{5.12}$$

A useful design strategy is to set $R_1 = m \cdot R$, $R_2 = R$, $C_1 = C$ and $C_2 = n \cdot C$. Replacing this values in Equation 5.10 gives a new Equation 5.13.

$$Q = \frac{\sqrt{m \cdot n}}{m + 1 - m \cdot n} \tag{5.13}$$

The quality factor of a Sallen-Key filter is influenced by the gain (k) and defines the dB gain on the cutoff frequency, ideally this factor should be closer as possible to $\frac{\sqrt{2}}{2}$??. Setting a arbitrary value of $m = 2$, the ideal value of $Q = \frac{\sqrt{2}}{2}$ and using Equation 5.13 it is possible to calculate a $n = 0,6771$. It is possible to simplify Equation 5.12 using the same method used to simplify Equation 5.10 to 5.13. Using this method will produce Equation 5.14 that will be used to determine the $R \cdot C$ constant that will be later used to define the resistors and capacitor values of our filter.

$$R \cdot C = \frac{1}{2 \cdot \pi f_c \cdot \sqrt{m \cdot n}} \tag{5.14}$$

Using the previously calculated values for m, n, f_c and Equation 5.14 wil give us a $R \cdot C = 3.50115 \cdot 10^{-5}$. Setting a arbitrary value of $R = 10 \cdot 10^3$ will lead to $C = 3.5 \cdot 10^{-9}$. Using the relations: $R_1 = m \cdot R$, $R_2 = R$, $C_1 = C$ and $C_2 = n \cdot C$ and the commercial resistors and capacitors values from (BURGESS, 2015), will produce the following values: $R_1 = 22k\Omega$, $R_2 = 10k\Omega$, $C_1 = 3900pF$ and $C_2 = 2700pF$. If theese values are used in Equations 5.10 and 5.12, we will have a quality factor of 0.7359 and a cutoff frequency of 3306.6986kHz, both which are close from the ideal ones.

5.2.4 Final Circuit

Based on all the previously calculations and on (TEXAS INSTRUMENTS, 1999), the final circuit will be the one in Figure 23. R60 was added to reference the input to ground and R58 was added to limit the amount of current that can flow from the MCU and the DAC circuit. R55 was added to prevent undesired currents to flow from the circuit output to the OPAMP, R59 is used to reference the output to GND and TZ8 is a TVS used to prevent any ESD or voltage spikes (LEPKOWSKI; LEPKOWSKI, 2006) to enter the board from the *Speed Reference Output Channel*.

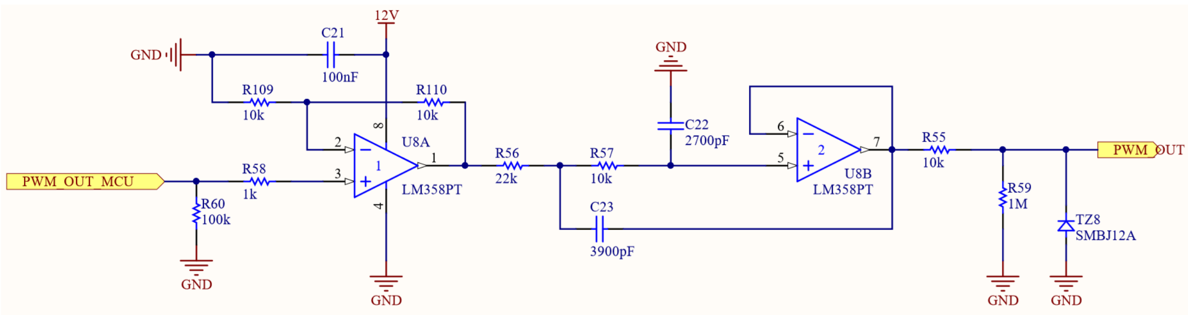

Figura 23 – PWM to Speed Reference Circuit

5.3 Hardware Interface Between Microcontroller and Computer

5.3.1 USB and UART

Nowadays most computers do not have a serial port connector (EETIMES, 2013), the majority of communications with peripherals are done through USB ports. The choosen microcontroller for this project (as discussed on Section **??**) does not have USB interface, only UART.

As it was explained in Sections 2.4.10.2 and 2.4.10.3, USB communication protocol is half-duplex, UART protocol is full-duplex though. While USB is composed of a differential pair of data wires, UART has one wire for receiving and another one for transmitting information.

In order to make this project compatible with most of modern computers, there is the need to have a USB to UART converter circuit.

5.3.2 Conversion Circuit

The issue discussed in the previous section is not a new thing, so there are loads of integrated solutions to solve this issue (RESEARCH, 2008). The choosen one was the Microchip's MCP2221A (MICROCHIP, 2016), this is a USB to UART/I^2C converter chip, it emulates a virtual serial port on the computer, making it possible to communicate with the microcontroller UART ports just using a pair of capacitors and a resistor as Figure 24 shows.

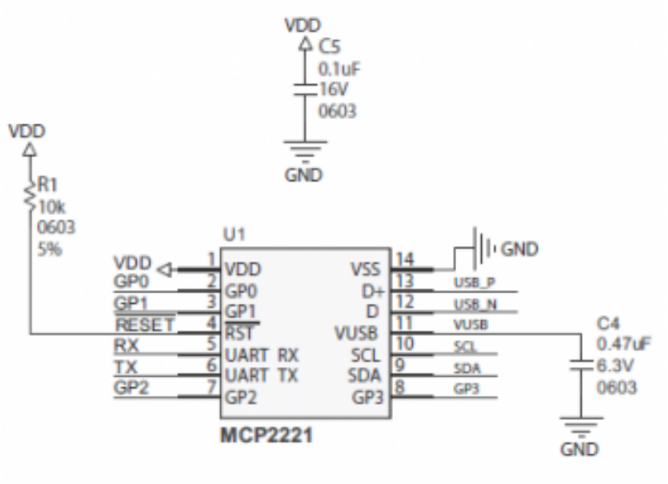

Figura 24 – MCP2221A basic circuit (MICROCHIP, 2010)

This chip already contains a internal 3V3 LDO in order to convert the 5V TTL level to the 3V3 standard level for USB data lines.

5.3.3 Circuit Protection

In order to ensure reliability on the circuit, ESD protection is needed, every connection between the circuit board and the outside world has the potential to pick unwanted noise and ESD, and USB is not exclued from that problem (LITTLELFUSE, 2010).

High-frequency noise could be filtered using low pass filters in both data lines using discrete passive components. Moreover, the data lines could be protected from ESD using discrete TVS. The number of discrete componentes needed to filter and protect the lines makes a discrete-component-solution unpractical, expensive and spacious. Nowadays there are unexpensive integrated solutions in order to save space on the PCB, one of them is the ON Semiconductor STF202-22T1G. This IC is a USB Filter with ESD protection, as the datasheet (ON SEMICONDUCTOR, 2012) says: *"This device is designed for applications requireing Line Termination, EMI filtering and ESD protection"*, making it more than ideal for this project. The STF202-22T1G internal circuit can be seen on Figure 25.

5.3.4 Complete Circuit

For the final circuit the STF202-22T1G was connected before the MCP2221A in order to protect and filter the data lines. Moreover, two external resistors were added to the serial communication lines (based on the Arduino Rev3 Schematic (ARDUINO, 2010)). Figure 26 contains the final circuit.

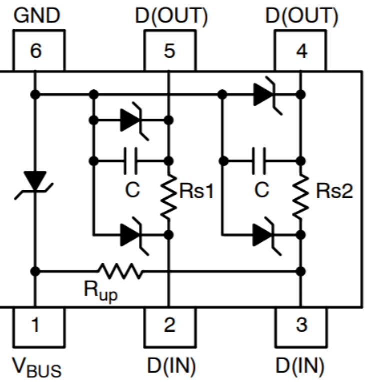

Figura 25 – STF202-22T1G Internal Circuit (ONSEMI, 2012)

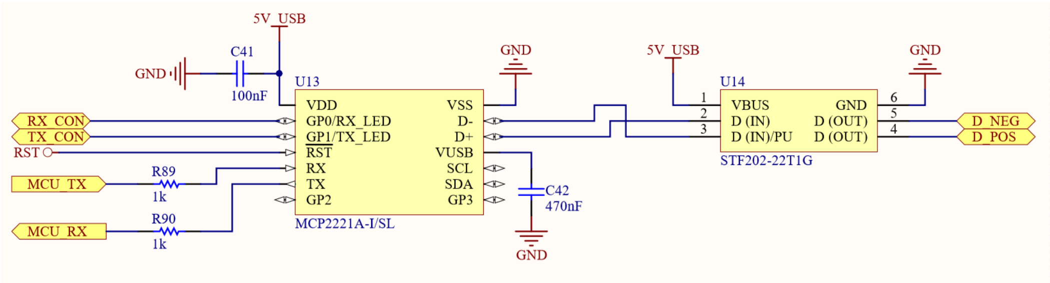

Figura 26 – USB/UART Converter Circuit (GUIMARAES, 2018c)

The *TX CON* and *RX CON* lines are used in other to indicate when the MCP2221A chip is repectively transmitting or receiving data. This lines drain current when data is transmitted or received and are used to blink LEDs in other parts of the circuit board.

Both capacitors are decoupling capacitors for the 5V and 3V3 lines.

6 Software Project

This project has two layers of software that communicates with each other, the microcontroller program and a program executing in a computer. There were some functionalities that could be implemented on either layers, as the computer hardware is obviously superior than the microncontroller hardware everything that could be implemented in either layers was implemented in the computer software.

6.1 Microcontroller Code

6.1.1 Microcontroller programming basics

Microcontrollers were traditionally programmed using Assembly language, nowadays we have a different scenario though. With the advancement of compilers, today it is most common to write the code for a microcontroller in C language and let the compiler translate it to a binary assembly format (MAZIDI; NAIMI; NAIMI, 2010). A convinient reason to use C is that it is one of the most efficient programming languages in terms of execution speed, this happens because it was designed to efficiently map typical machine instructions (KERNIGHAN; RITCHIE, 2006), so considering real-time constrains and other execution constrains in microcontrollers it is a excelent fit.

A microcontroller code is composed basically of two parts:

- *Setup:* This part of the code is only executed once, as the name may indicate, it is used to set properties, configure timers, inputs and other features of the hardware.
- *Loop:* This part of the code is executed continuously or until some condition is reached.

Other important component of a microcontroller code are interruptions. It is possible to interrupt the standard execution of a program when a event happens, or as it is more common to say, when a event triggers a interruption. This event may be a timer overflow, a event triggered by an input change among other things. Interrupt routines are really useful when working with intrumentation and timers, because using interruptions it is feasible to meet real-time requirements in a project (MUKARO; CARELSE, 1999).

6.1.2 Microcontroller Code Map

The Figure 27 show a functional map of the microcontroller code that can be found entirely in Appendix A.1.

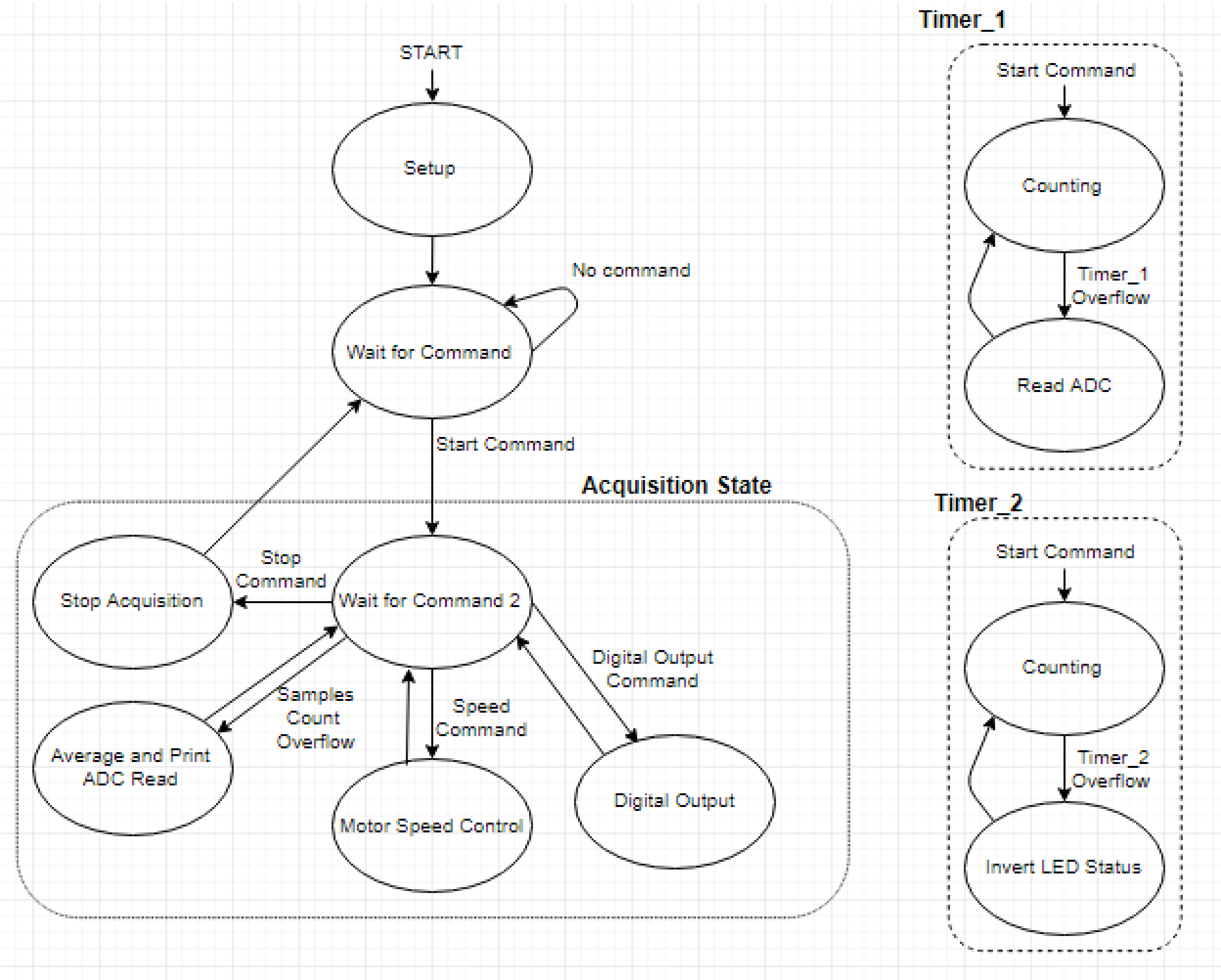

Figura 27 – Microcontroller Code Map (GUIMARAES, 2017b)

As soon as the microcontroller is turned on it enters in the *Setup*, on this part the following things are setted:

- *Timer_1:* Timer_1 max count value is setted and a interruption service routine is appointed.
- *Timer_2:* Same thing done for Timer_1 is done for Timer_2.
- *Serial Port:* The serial port baud rate is defined and the serial port is opened.
- *Port definitions:* The I/O ports are defined as inputs (high impedance) or as outputs (low impedance).

After setting up the code enters in a state in which it waits for a *Start Command* from the computer. This command starts Timer_1 and makes the code enter the *Acquisition State*. Everytime Timer_1 finishes its count a ISR will be triggered, all the analog inputs will be read (sampled) and stored followed by the timer restarting its counting process. The *Start Command* also starts Timer_2, this timer operates the same way as Timer_1, the difference is that its ISR will only toggle the acquistion LED state.

In the acquistion state, if a *Digital Output Command* is received the code will decrypt this command (this is actually a group of possible commands) and set the digital outputs according to the decrypted message.

A received *Speed Command* instruction will make the code behave in a similar way than *Digital Output Command*, code will decript the command (it also is a group of possible commands) and output a corresponding PWM value in the analog output port in order to control the electric motor speed.

During all the *Acquisition State*, everytime Timer_1 ISR does a presetted number of reads, the code makes an average of thoose reads and will send them through the serial port to the computer. After that the code will reset the number of read samples and start to count samples again. Another useful feature is that during all the *Acquisition State* the code is also continuosly reading the microcontroller digital inputs, this inputs are used to detect if a sensor is not connected, if any of the sensors is considered to be disconnected instead of sending the analog reading from the respective sensor input, the code will send a “-1” value to the computer. This way the computer software that the one responsible for treating this event and take the appropriate action.

The code will exit the *Acquisition State* if the computer sends a *Stop Command*. This will also set all digital outputs to a low logic level and will disable both timers interruption service routines. The code will go back to the *Wait for Command* state and wait for a *Start Command* to restart acquisition.

This code architecture was designed in order to make the microcontroller code as simples as possible in order to make execution faster to avoid jeopardizing the real-time constrain. The same code is used during brake tests, during acquisition and any other process. As mentioned before, all the heavy data processing is done by the computer software.

6.2 Computer Software

6.2.1

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Appendix

APPENDIX A – First Appendix

A.1 Micontroller Code

```
//Libraries
#include <TimerOne.h>
#include <MsTimer2.h>
#include <math.h>

//HW DEFINITIONS
//Digital ports
///inputs
#define ADC_CON_0           2
#define ADC_CON_1           3
#define ADC_CON_2           4
#define ADC_CON_3           6
#define ADC_CON_4           7
#define ADC_CON_5           8
///outputs
#define DIG_OUT_PORT_0      9
#define DIG_OUT_PORT_1      10
#define RELAY_OUT_0         11
#define RELAY_OUT_1         12
#define ACQ_LED             13

//Analog Ports
#define PWM_OUT             5


//COMMUNICATIONS DEFINITIONS
#define START_ACQ_BYTE      21
#define STOP_ACQ_BYTE       22
#define MASTER_RESET_BYTE   23
#define NULL_DIGITAL_BYTE   96
#define MAX_DIGITAL_BYTE    111
#define NULL_SPEED_BYTE     155
```

```
#define MAX_SPEED_BYTE          255


//GENERAL DEFINITIONS
#define SET                     1
#define RESET                   0
#define ACQ_LED_BLINK_MS        250
#define SAMPLE_RATE             10
#define NUMBER_OF_SAMPLES       100


//GLOBAL VARS
static boolean acquisitionEnabled=false;
int samples=RESET;
short DIGITAL_OUT_PORTS[]={DIG_OUT_PORT_0,DIG_OUT_PORT_1,RELA
short DIGITAL_IN_PORTS[]={ADC_CON_0,ADC_CON_1,ADC_CON_2,ADC_C

boolean digitalInstruction={RESET,RESET,RESET,RESET};
static float sensorData[]={RESET,RESET,RESET,RESET,RESET,RESE


//Function to write to digital ports
void digitalOutputControl(){
        for(int i=RESET;i<NUMBER_OF_DIGITAL_PORTS;i++){
                digitalWrite(DIGITAL_OUT_PORTS[i],digitalInst
        }
}

//Function to set all digital outputs to low
void resetDigOutputs(){
        for(int i=RESET;i<NUMBER_OF_DIGITAL_PORTS;i++){
                digitalInstruction[i]=RESET;
        }
        digitalOutputControl;
}

//Function to configure Timer 0 - PWM-OUT
void configureTimer0(){
        TCCR0B = (TCCR0B & 0b11111000) | 0x01;
```

```
}

//Function to configure Timer 1 - ACQUISITION
void configureTimer1(){
        Timer1.attachInterrupt(timer1_OISR);
        Timer1.initialize(SAMPLE_RATE);
        Timer1.stop();
}

//Function to configure timer 2 - LED
void configureTimer2() {
        MsTimer2::set(ACQ_LED_BLINK_MS, timer2_OISR);
}

//Timer 1 overflow interruption routine
void timer1_OISR(){
        if (samples<NUMBER_OF_SAMPLES){
                if(enableAcquisition==true){
                        //Lendo dado analogico
                        sensorData[0]=sensorData[0]+analo
                                sensorData[1]=sensorData[
                                sensorData[2]=sensorData[
                                sensorData[3]=sensorData[
                                sensorData[4]=sensorData[
                        sensorData[5]=sensorData[5]+analo
                        samples++;
                }
        }
}

//Timer 1 overflow interruption routine
void timer2_OISR(){
        if(enableAcquisition){
                digitalWrite(ACQ_LED_PIN, digitalRead(ACC
        }else{
                        digitalWrite(ACQ_LED_PIN, LOW);
        }
}
```

```
//Function to write adc results in serial port
void printResults(int * result){
        Serial.print(result[0]);
        Serial.print(",");
        Serial.print(result[1]);
        Serial.print(",");
        Serial.print(result[2]);
        Serial.print(",");
        Serial.print(result[3]);
        Serial.print(",");
        Serial.print(result[4]);
        Serial.print(",");
        Serial.print(result[5]);
        Serial.print(".");
}

void IOsetup(){
        pinMode(ACQ_LED_PIN,OUTPUT);

        for(int i=0;i<6;i++){
                if (i<4){
                        pinMode(DIGITAL_OUT_PORTS[i],OUTPUT)
                }
                pinMode(DIGITAL_IN_PORTS[i],INPUT);
        }

}

void setup(){
        Serial.begin(9600);
        IOsetup();
        digitalWrite(ACQ_LED_PIN,LOW);

        configureTimer0();
        configureTimer1();
        configureTimer2();
        MsTimer2::start();
}
```

```
void loop(){
        if (samples>=NUMBER_OF_SAMPLES){
                Timer1.stop();
                static int resultAcq[6];

                for(int k=0;k<6;k++){
                        resultAcq[counter] = (int)roundf(
                        sensorData[counter]=RESET;
                }
                samples=RESET;
                Timer1.restart();

                printResults(resultAcq);
        }

        if(Serial.available()){

        char.byteRead = Serial.read();

        switch(byteRead){

                case START_ACQ_BYTE:{
                        if (!acquisitionEnabled){
                                acquisitionEnabled=true;
                                samples=RESET;
                                Timer1.restart();
                        }
                }
                break;

                case STOP_ACQ_BYTE:{
                        acquisitionStop();
                }
                break;

                case MASTER_RESET_BYTE:{
                        acquisitionStop();
                        resetDigOutputs();
                }
```

```
                                        break;

                                        default:{
                                                if (byteRead>=NULL_SPEED_BYTE){
                                                        unsigned char speed_byte = by
                                                        speed_byte-=NULL_SPEED_BYTE;
                                                        int speed=RESET;
                                                        speed = 1023*speed_byte/(MAX_
                                                        analogWrite(PWM_OUT, speed);

                                                }else if ((byteRead>=NULL_DIGITAL_BYT
                                                        for (int i = 3; i>-1; i--) {
                                                                                digit
                                                                        }
                                                                digitalOutputControl(
                                                }
                                        }
                                        break;
                        }
        }
```