University of Brasília – UnB
Faculty UnB Gama – FGA
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

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

Chapter 2: Chapter 3: Chapter 4: Chapter 5:

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

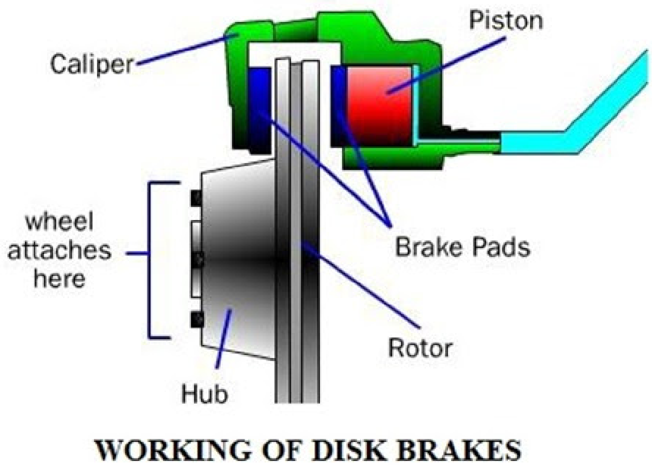

Figura 1 – Schematic for disk brake systems

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.

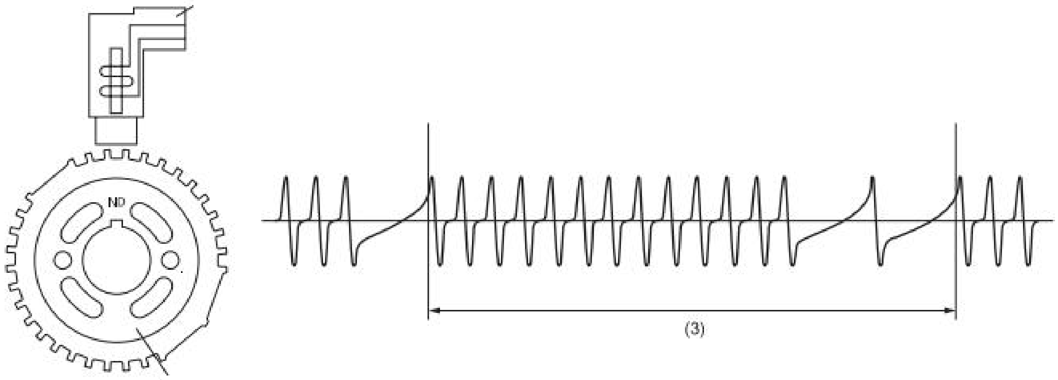

Figura 3 – Magnetic Sensor Signal (DESCONHECIDO, 2016a)

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 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).

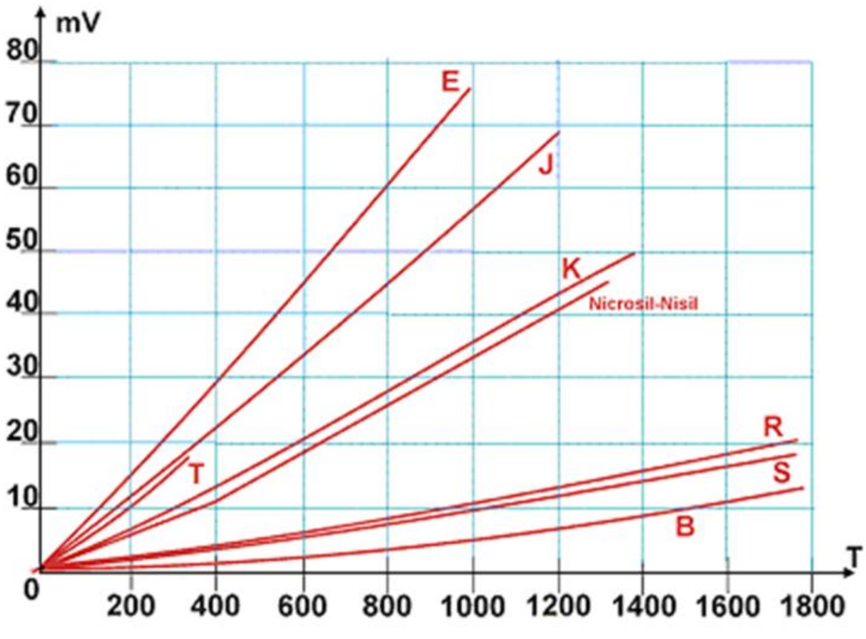

Figura 4 – Thermocouple characteristic voltage output (UNKWNON, 2016)

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).

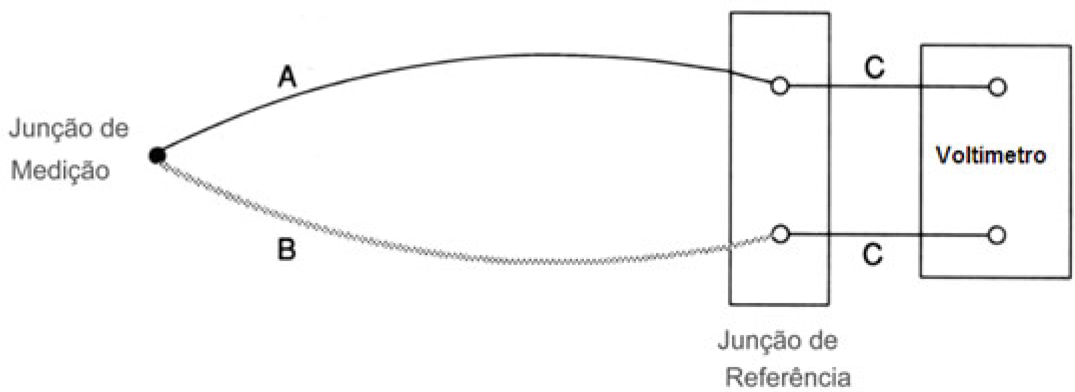

Figura 5 – Thermocouple Measurement (ECIL, 2016)

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

Tabela 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).

Figura 6 – Distension (INSTRUMENTS, 2016a)

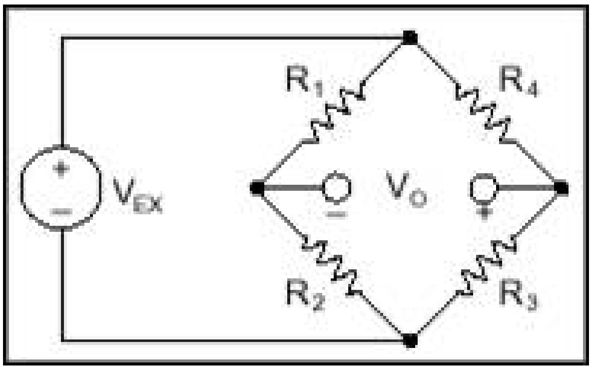

Figura 7 – Wheatstone bridge (INSTRUMENTS, 2016b)

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

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

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.

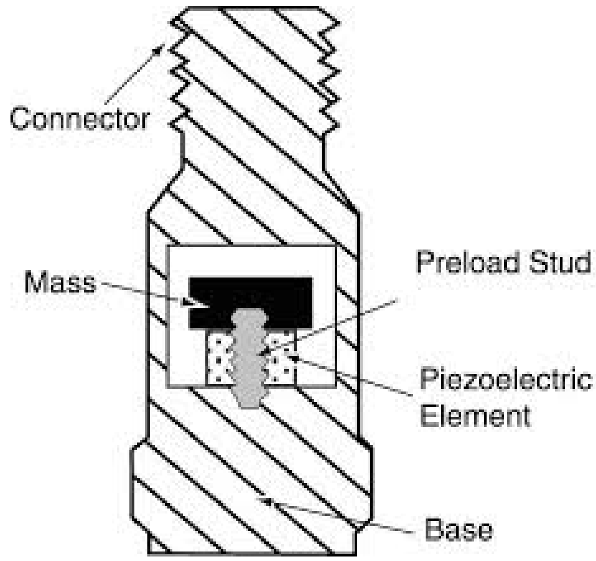

Figura 8 – Piezo Accelerometer (UK, 2016)

By measuring this variation of electrostatic force or electrical voltage it is possible to determine the acceleration that the sensor has undergone. In Figure ref figpiezoAccelerometer 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, 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 (**??**). Figure 9 shows the schematic symbol of the OpAmp.

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.

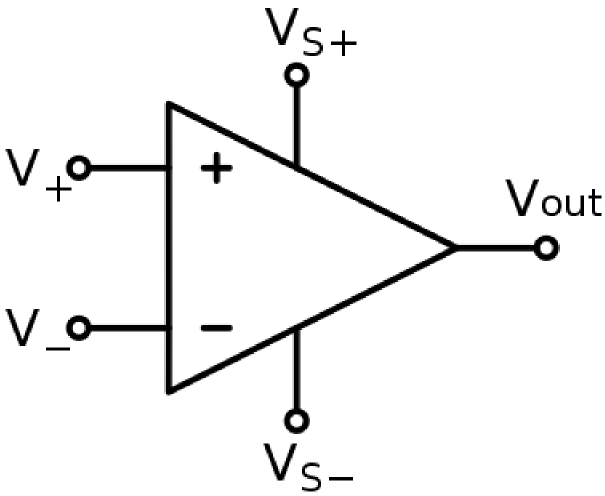

Figura 9 – Operational Amplifier (OMEGATRON, 2007)

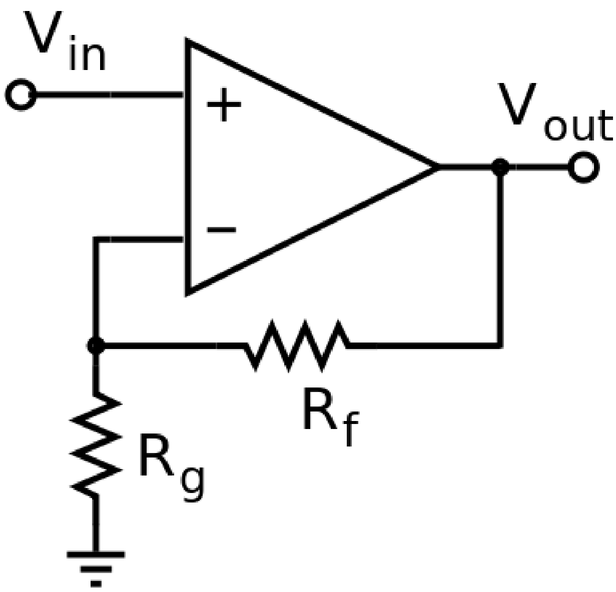

Figura 10 – Operational Amplifier (SALURI, 2009)

The output voltage of this amplifier is given by Equation 2.4.5.2

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

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).

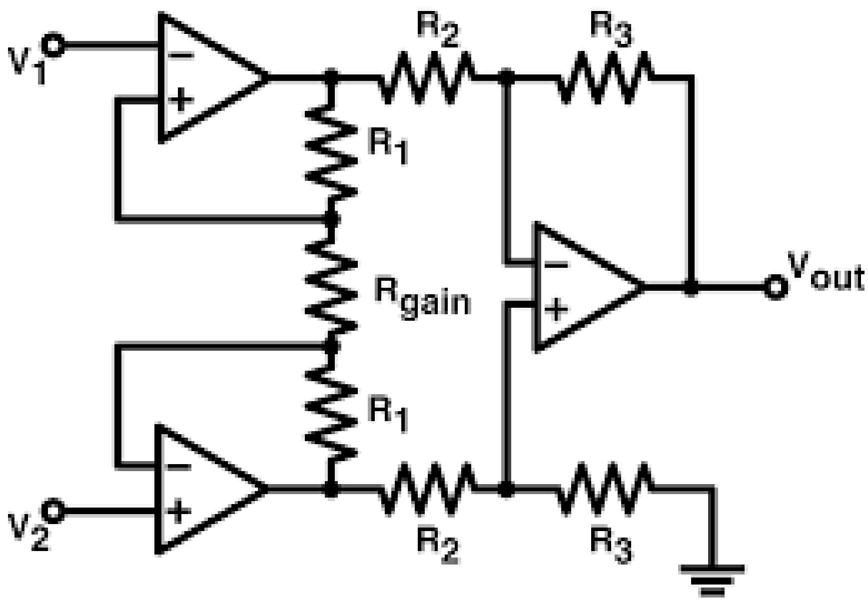

Figura 11 – Instrumentation Amplifier (DESCONHECIDO, 2016b)

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.

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

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.

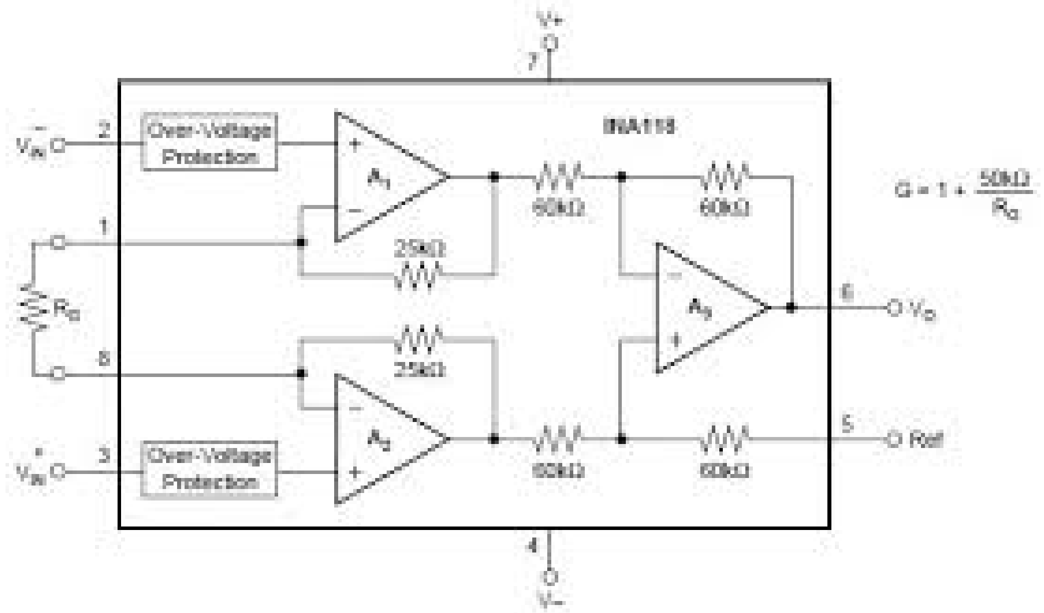

Figura 12 – INA 118 (INSTRUMENTS, 2000a)

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) .

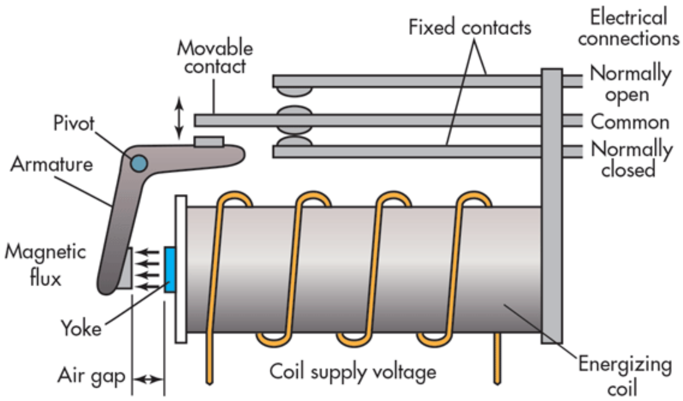

Figura 13 – Schematic Relay (TESCHLER, 2016)

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, 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).

3 Methodology

3.1 Study Stages

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

3.1.1 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.

3.1.2 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.

3.1.3 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 ashes, 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 reaching it's goals.

4 Project Requirements

4.1 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 rate 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.

4.2 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.

4.3 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.

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 14.

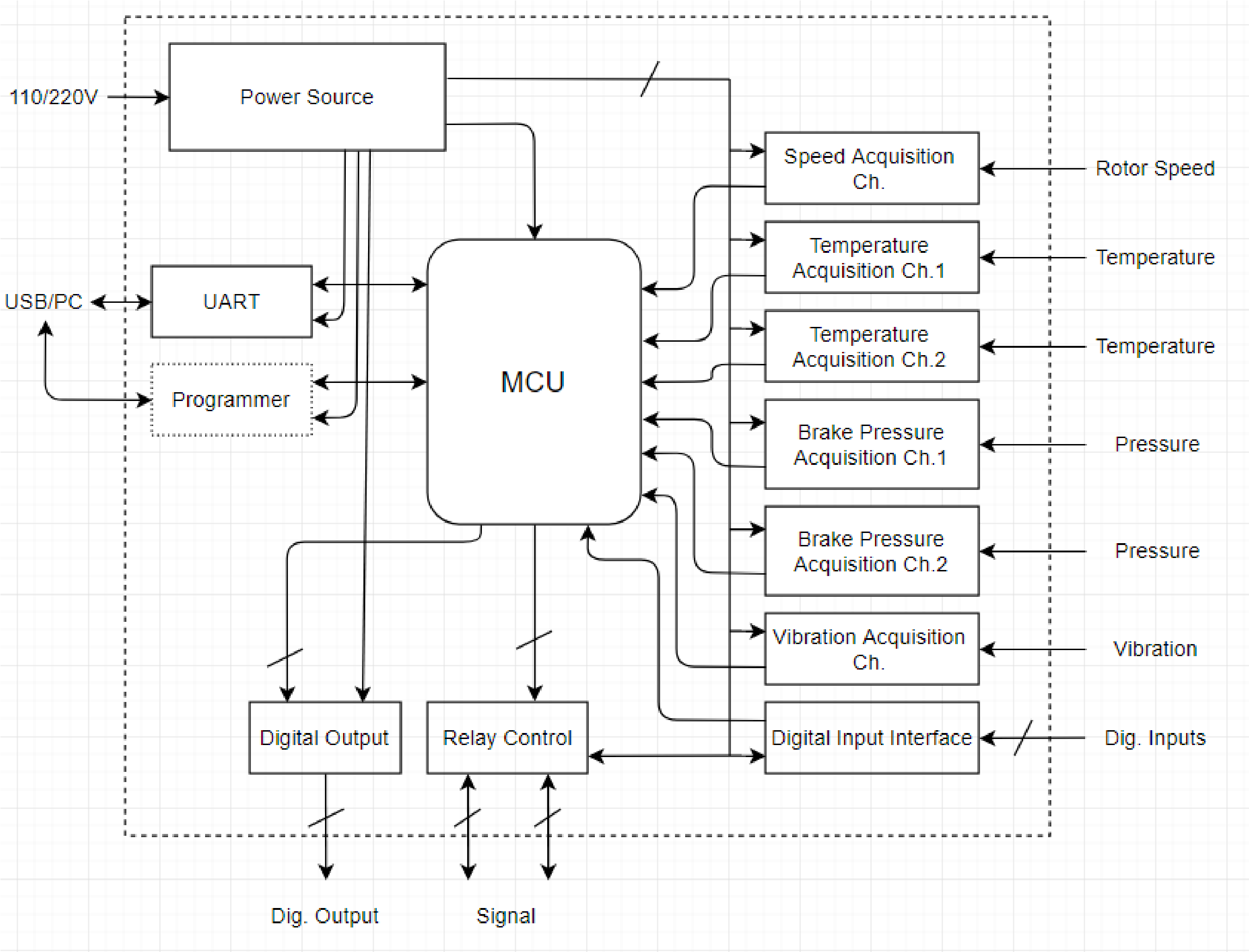

Figura 14 – Hardware Project Architecture (GUIMARAES, 2017)

5.1 MCU

The system will be microcontrolled rather than microprocessed because this is the most practical way to ensure that the real-time constrain will be respected. The choosen microcontroller is the *ATmega328p* developed by *Atmel Corporation* with 32 Kb of flash memory, 1 Kb of *EEPROM* (Electrically Erasable Programmable Read-Only Memory), 32Kb of *SRAM* (Static Random Access Memory) and a 16 MHz clock. This microncontroller is widely used in academic environment (specially after the Arduino project started, when microncontroller programming became much more feasible and reachable), and is famous for being easy and reliable to use. The *ATmega328p* has six ADC inputs with a resolution of 10 bits and more 14 GPIO ports. This microcontroller also has serial communication, I^2C communication and other convinient features. It is really versatile and more important it meets this project requirements. The Figure 15 shows the pinage of this device in it's most commom footprint (DIP28).

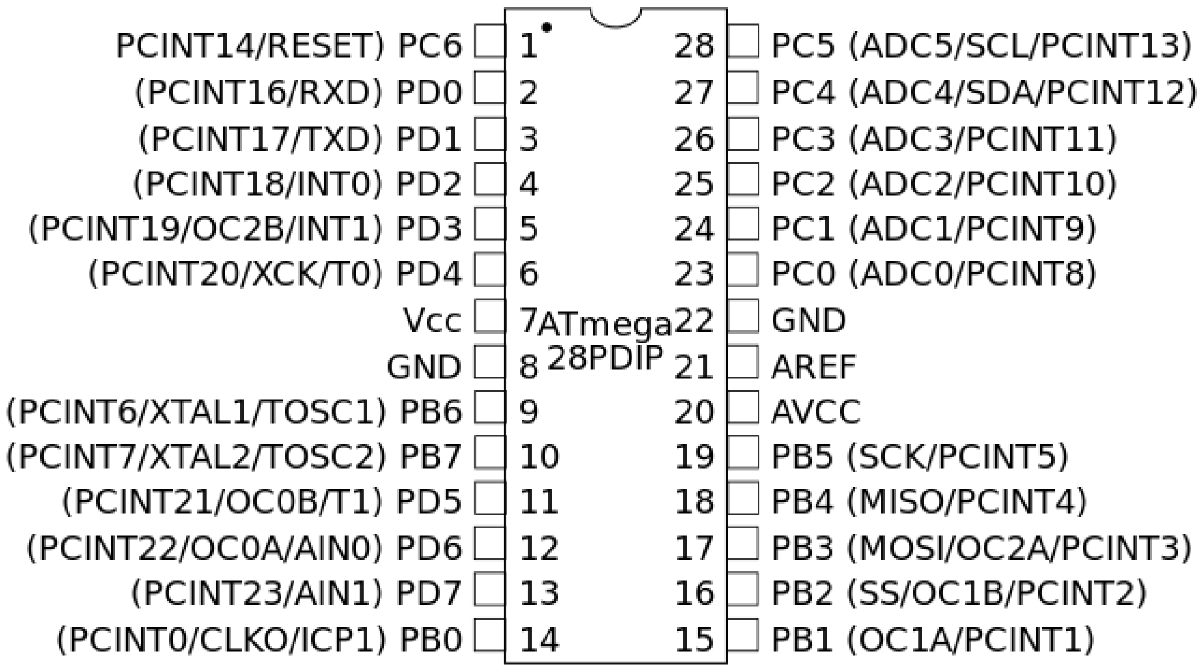

Figura 15 – *ATmega238p* (COORPORATION, 2011)

5.2 Temperature Acquisition Channel

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 - °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.

5.3 Brake Pressure Acquisition Channel

A very influential parameter in a braking system is the pressure that the brake exerts on the rotor. Pressure is a magnitude measured in Pascal and can be expressed by the force ratio by the area. There are some sensors based on the piezoelectric effect, but the most accurate way to measure force is by using load cells.

Load cells have very low output levels, of the level of 2mV/V, and therefore an amplification is fundamental. It is not necessary to know the nature of the strain gauges when a load cell is being calibrated since generally the manufacturers provide a calibration curve based on the signals V_O and V_{EX} of the Figure 7, it is worth noting that these signals can not have the same reference, otherwise it will not be possible to excite the wheatstone bridge correctly.

The most common way to amplify the signal of a load cell is using a instrumentation amplifier. Although it is a widely used configuration, assembling this amplifier using three different operational amplifiers and seven resistors as in Figure 11 may make it inaccurate due to manufacturing imperfections of the components. Another factor that greatly influences the output signal of a load cell is the excitation voltage of its wheatstone bridge, if it varies too much the output will vary greatly as well, which will hamper its calibration.

In order to solve these two problems there is a solution widely used in the market which is the *INA125* of Texas Instruments, this CI besides performing signal amplification also provides a very precise excitation source for the wheatstone bridge, the only component required to be coupled is a resistor R_G, as shown in Figure 16. This resistor will determine the gain for the amplification according to the equations 5.1 and 5.2:

$$V_O = (V_{IN}^{+} - V_{IN}^{-}) \cdot G \tag{5.1}$$

$$G = 4 + \frac{60k\Omega}{R_G} \tag{5.2}$$

Taking into account the sensitivity of 2mV/V, this means that if the cell is excited with 10V, its output will vary from 0 to 20mV. Since the analog input of the chosen microcontroller (Atmega328) is 0 to 5V, we may to amplify the cell output signal by a factor of 250 to increase precision. Using Equation 5.2, to obtain a gain of amplification ratio of the ideal R_G would be 243Ω, a resistor of this value is not commercially available, the closest ones would be 240Ω and 270Ω. The first would cause a gain greater than 250 and consequently an IC output voltage greater than 5V when the cell had an output voltage of 20mV. The resistor 270Ω will generate a gain of 226 and cause the CI output

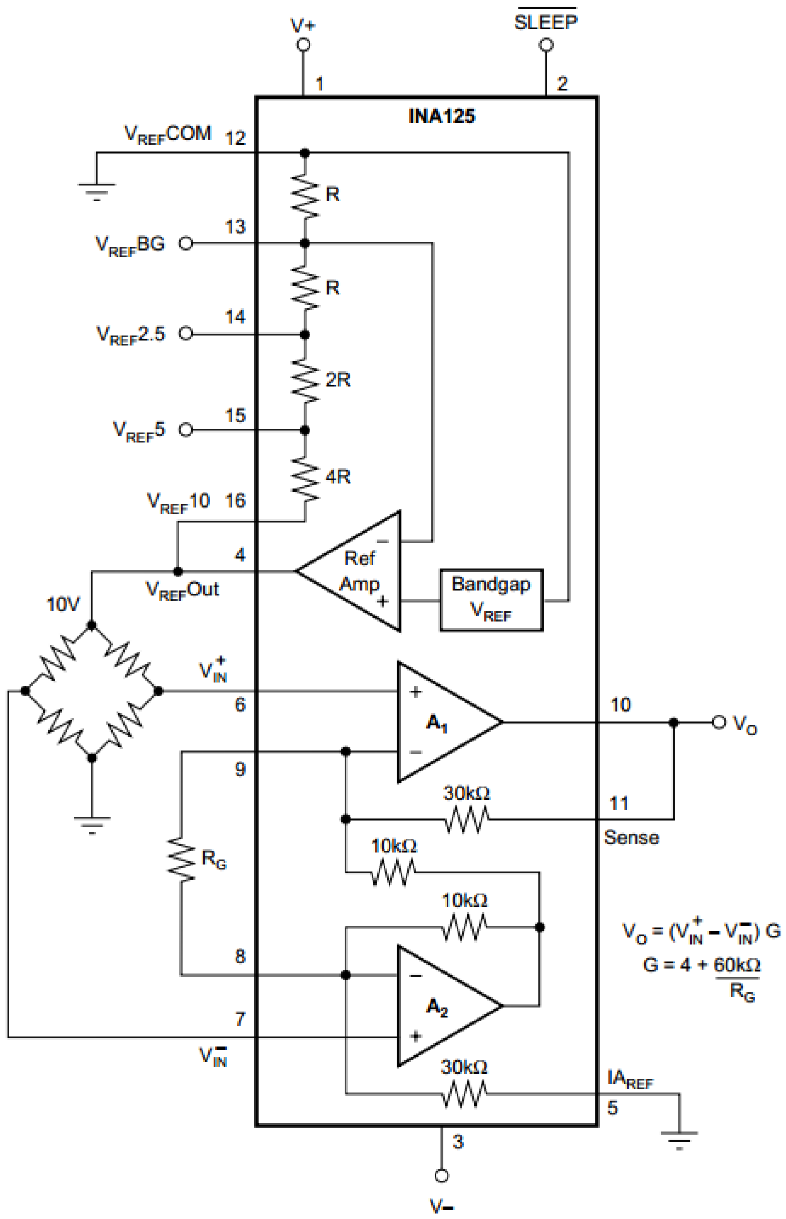

Figura 16 – INA125 Schematic (INSTRUMENTS, 1998) to range from about 0V to 4.52V, using 90.4% of the resolution of the microcontroller input.

Figure 17 shows the schematic of the charge cell conditioning circuit with the Texas Instruments INA125 IC.

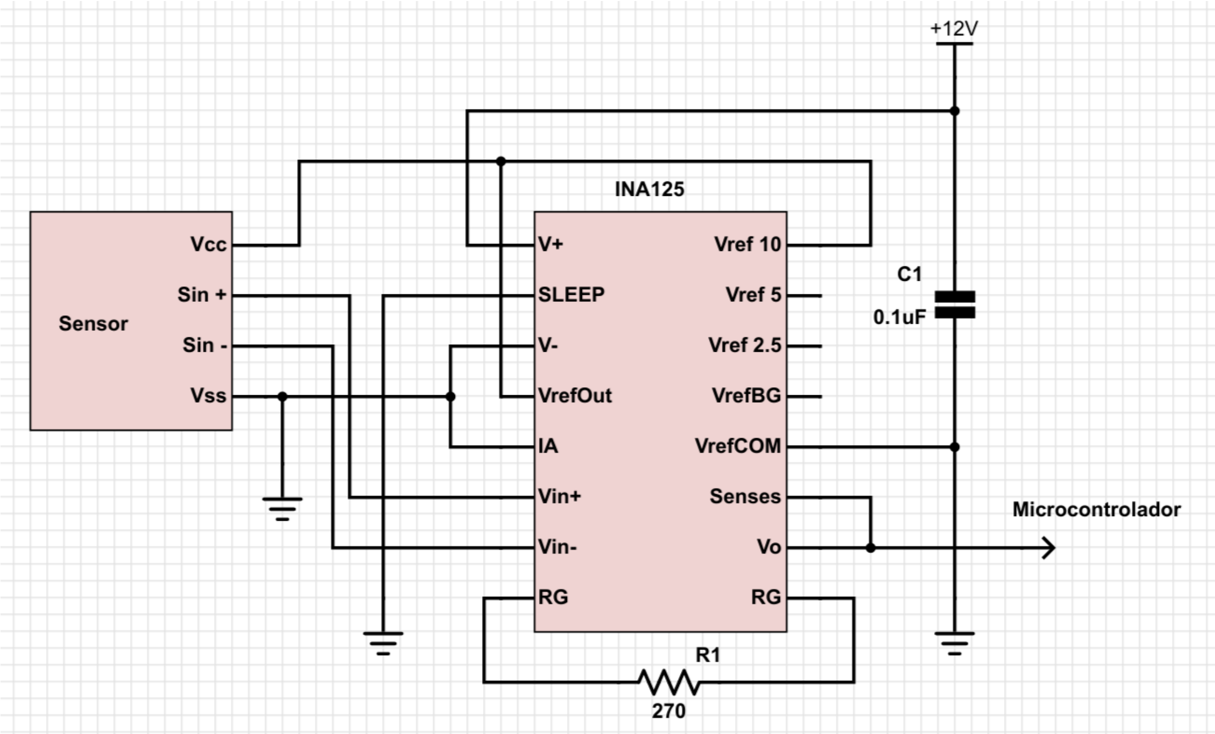

Figura 17 – Conditioning Circuit for the Load Cell

5.4 Speed Acquisition Channel

5.4.1 CKP Signal Condition

5.5 Acceleration Acquisition Channel

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 Software

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 **??** gives a overral idea of the microcontroller code that can be found in ....

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

- *Timer 1:* Timer one is used for controlling acquisition sampling rate, i.e., the interval between each acquisition. Each moment that this timer overflow its count, a interruption is triggered and the analog inputs are read (sensor signals) and stored. In the setup block only the timer clock frequency and the maximum value are defined.
- *Timer 2:* This timer is used only to control the blinking frequency of a LED used to indicate if a execution is happening.
- *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).

6.2 Computer Software

6.2.1

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Appendix

APPENDIX A – First Appendix

Texto do primeiro apêndice.

APPENDIX B – Second Appendix

Texto do segundo apêndice.

Annex

ANNEX A – First Annex

Texto do primeiro anexo.

ANNEX B – Second Annex

Texto do segundo anexo.