Prototyping and calibration of a low-cost stroboscope: an educational experiment in mechatronics

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Abstract

This work aims to develop a stroboscope, which consists of an optical equipment capable of generating flashes of light at different frequencies, allowing to determine and study the body rotation velocity, whereas the frequency of the rotation movement is the same frequency of light pulses, the process will appear stationary. This phenomenon is called stroboscopic effect, a visual event that occurs when a continuous movement is presented by a series of samples, generated by flashes of light. The stroboscope's electronic part is based on the Arduino platform and the LED technology, while the mechanical part is based on prototyping in 3D printing. The final prototype is low-cost, which goes through calibration and validation processes, the rotation velocity of a three-phase motor was measured and the stroboscope achieved a performance very similar to the commercial tachometer. Initially, this work consisted of using a first stroboscope prototype in a summer course called Summer Camp at the Polytechnic Institute of Bragança as a way to teach high school students to program microcontrollers. This part of the work is based on STEAM education (Science, Technology, Engineering, Arts, Math), which integrates all these concepts as a study methodology, aiming at the implementation of practical projects and challenges, encouraging students to learn technology and develop critical thinking skills. At the end of the course, the students could learn how to program Arduino based on the physical device features, developing skills in STEAM areas.

Keywords: stroboscope, electronics, microcontrollers, prototyping, STEAM.

Resumo

Este trabalho tem como objetivo o desenvolvimento de um estroboscópio, um equipamento óptico capaz de gerar flashes de luz em diferentes frequências, permitindo determinar e estudar a velocidade de rotação de um corpo, visto que quando a frequência do movimento de rotação estiver na mesma frequência dos impulsos de luz, o processo parecerá estacionário. Esse fenômeno é denominado efeito estroboscópico, um evento visual que ocorre quando um movimento contínuo é apresentado por uma série de amostras, geradas pelos clarões de luz. A parte eletrônica do estroboscópio é baseada na plataforma Arduino e a na tecnologia LED, enquanto que a parte mecânica é baseada na prototipagem em impressão 3D. O protótipo final é de baixo custo, o qual passa por processos de calibração e validação, a velocidade de rotação de um motor trifásico é medida e o estroboscópio alcança um desempenho muito semelhante ao de um tacômetro comercial. O primeiro protótipo do estroboscópio foi utilizado em um curso de verão chamado Summer Camp no Instituto Politécnico de Bragança, como forma de ensinar alunos de escolas secundárias a programar microcontroladores. Essa parte do trabalho foi baseada na educação STEAM (Ciência, Tecnologia, Engenharia, Artes, Matemática), a qual integra todos esses conceitos como uma metodologia de estudo que visa a implementação de projetos e desafios práticos, incentivando os alunos a aprender tecnologia e desenvolver competências de pensamento crítico. No fim do curso, os alunos puderam aprender como programar o Arduino baseado nas características de um dispositivo físico, desenvolvendo conhecimentos nas áreas STEAM.

Palavras-chave: estroboscópio, eletrônica, microcontroladores, prototipagem, STEAM.

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Acronyms

2D Two Dimensions. 18

3D Three Dimensions. 2, 5, 17, 30

CAD Computer Aided Design. 2, 17, 18, 30

CBL Challenge Based Learning. 3, 52, 53, 64

CT Computational Thinking. 3, 51, 52, 64

DC Direct Current. 17

FDM Fused Deposition Modeling. 19

IDE Integrated Development Environment. 26, 34, 54

IPB Polytechnic Institute of Bragança. 52, 53

LCAR Control, Automation and Robotics Laboratory. 33

LCD Liquid Crystal Display. 26

LDR Light Dependent Resistor. 17, 30, 46

LED Light Emitting Diode. 2, 10, 13–16, 20, 26

LOM Laminated Object Manufacturing. 19

MOSFET Metal–oxide–semiconductor field-effect transistor. 27, 38

PCB Printed Circuit Board. 33, 42

PDF Portable Document Format. 42

PLA Polylactic Acid. 30, 45

RPM Rotations Per Minute. 10, 14, 15, 25, 31, 36

SLA Stereolithography Apparatus. 19

SLS Selective Laser Sintering. 19

STEAM Science, Technology, Engineering, Art, Math. 2

USB Universal Serial Bus. 28

Chapter 1

Introduction

In the industry is very common the applying of resources and machines for implementation of the processes and creation of the products. For this reason, the measurement and control of such processes are essential to achieve better performance, efficiency, and consequently best quality, as well as, monitor the operation of the equipment, identify failures and ensure the security for the industry and the employees.

The measure instruments are the set of tools used with the objective of obtaining data about the particular processes. In general, these devices measure features like pressure, temperature, velocity, humidity, vibration, and are widely applied in machines such as motors, heaters, reactors, refrigerators, air conditioners, compressors, ovens, and other equipment. It's important to obtain the periodic calibration of these instruments so that the results obtained through them be reliable and accurate [1].

1.1 The relevance of the theme

The inspection and evaluation of equipment that work through continuous or periodic movements need to be done while it is in operation. Some devices such as automobiles, motors, propellers, textile looms, electric razors, blenders, and blowers [2], when they exhibit some defect, the best way to identify the problem is with the device turn on. However, this task becomes difficult when the movement is in high frequency.

The solution for this problem is the use of a stroboscope, an optical physical device that consists of the emission of blinking light in different frequencies desired, allowing the study of the velocity of an object and visualizing details of the movement that the human eyes fail to see. When the frequency of the movement is equal to the frequency of light flashes, it seems that the movement is stationary and the equipment is stopped [3].

This instrument is based on the stroboscopic effect, a visual phenomenon that happens when a blinking light source glows an object in movement, generating a sequence of samples. Depending on the blink light frequency, the process can seem forward or backward, so it is important to coincide the frequencies to see the stationary image, which enables the study and the maintenance of moving parts with high frequency [4].

A way to develop a stroboscope is through the use of a microcontroller, as an instance the Arduino, responsible for processing all the information. All around the world, Arduino has been used to several projects, applications and to create low cost complex scientific equipment by students, artists, programmers, professionals, etc. Arduino is an electronics platform with hardware and software open-source, it is accessible and easy to use. Basically, the Arduino board is able to read sensors, buttons, messages and generate outputs such as controlling motors, Light Emitting Diode (LED)s or information [5]. Therefore, it is viable to use this platform in stroboscope development.

The device prototyping includes a mechanical design, where all the components are attached within a structure, which can be developed based on the 3D printing, one tool that has been widely used in device prototyping and is also known as additive manufacturing. This process is cheap, affordable and used to fabricate Three Dimensions (3D) objects through the creation of a virtual model of the object, usually done by Computer Aided Design (CAD) software. The 3D printing is based on layer by layer material deposition and the most common material used is the plastic [6].

The stroboscopes can also be used by students in modern educational experiments and research projects, as a way of learning physical, mechanical motion and technology [7]. Even more with the advent of Science, Technology, Engineering, Art, Math (STEAM) education, a study methodology that differs from the traditional teaching method and

aims at implementation of disciplines together with projects and practices to solve real-world problems [8].

1.2 Goals

The main goal aims the development and calibration of a low-cost stroboscope to be applied not only in the velocity measurement in the industry but in other areas, such as education. Besides hardware and software open-source allowing that other people can create their stroboscopes. For the creation of the prototype, some specific objectives were established:

- Analysis of existing market solutions;
- Development of the prototype's electronic part, including programming using Arduino platform and creation of electronic circuits;
- Development of the prototype's mechanical design, that is, the structure of the device, through the use of 3D printing.
- Utilization of the stroboscope to measure the rotation velocity of a three-phase motor and compare its performance with a commercial instrument.
- Application of stroboscope in STEAM education, as a way of assisting the teaching of mechatronics and technology for students from secondary schools, through the use of a physical device. Creating activities and challenges with the stroboscope, based on Challenge Based Learning (CBL) approaches and developing Computational Thinking (CT).

1.3 Dissertation structure

This document was developed in 7 chapters and its synopses are presented here. The Chapter 1 emphasizes the theme, its relevance and introduce some tools, followed by the

goals for the project development.

The Chapter 2 presents the state of art, that is, the bibliographic revision, all the study necessary to develop the device development, including the history, current stroboscopes, applications, operation, concepts, needed process, and advantageous tools.

The methodology is defined in Chapter 3, specifying the components and the methods chosen to manufacture the prototype, both the electronic part, the mechanical part, calibration, and validation.

All the development process to reach the final result is explained in Chapter 4, including the steps to develop the firmware, the hardware, the physical structure, and calibration.

The Chapter 5 describes the applying of the initial stroboscope prototype in a summer course at Polytechnic Institute of Bragança, within the scope of STEAM education.

The validation of the instrument and the test results are discussed in Chapter 6, and the final conclusion about the work in Chapter 7, followed by ideas for future work.

Chapter 2

State of Art

In this chapter, it will present, in the first section, a study about what is stroboscopy, some applications and how the stroboscopic effect works. The next section is devoted to the stroboscope as a physical device, its history and early devices followed by its applications and an analysis of the stroboscopes currently available on the market. It will also describe the importance of performing stroboscope calibration and how it can be performed.

The third section presents the concepts of 3D printing and how this method has been useful in prototyping 3D objects. Finally, the last topic will describe the advantages of using this physical device in the area of STEAM education, a new study methodology that has been applied in schools.

2.1 Stroboscopy

The stroboscopy allows analyzing movements in high frequency through illuminating the moving object with a light pulse source, representing the movement as a series of successive position images, producing the illusion of a slow or stopped motion [9], [10]. Since the 1830s, this procedure has been used in many applications including physics research and industrial manufacturing [11].

Currently, this technique is widely used to study and evaluate bodies with periodic movements, whether rotating, oscillating or vibrating, covering not only the field of

physics, electrical and mechanical but also medicine and education. It is also applied to observe objects trajectories through the use of stroboscopic photographs, cinematographic field and even as decoration at parties and concerts through stroboscope lights [4].

2.1.1 The stroboscopic effect

The stroboscopy is based on the stroboscopic effect, a visual phenomenon that occurs when a movement is presented as a series of samples. A periodic movement repeats at equal time intervals, that is, it returns to the same position after complete a specific period. If a pulse of light illuminates a periodically moving object always when it is in a single position, the object appears stopped and the movement frozen [12]. The stroboscopic effect was discovered in the 1800s [4] and can be observed when there is a synchronization between the frequency of light flashes and the frequency of movement [12].

For the visualization of the phenomenon, the light pulse length must be short enough compared with the periodic movement which intends to analyze, otherwise, image freezing may not be detected [12]. If the illumination frequency f1 is bigger than the frequency of movement f2, the body will appear to move backward, if f2 is bigger than f1, the body will appear to move forward, and if the frequencies coincide, the process will appear to be stationary.

Figure 2.1 represents an illustrative example of the stroboscopic effect through the use of a fan with a mark put on one of its propellers and a blink light source illuminating it. If the blink frequency is bigger than the rotation frequency, the first flash will illuminate the mark in an initial position, but the second flash will illuminate the mark in a backward position because at this moment the rotation movement hasn't completed a turn, that is, a period. This happens because the rotation frequency is slower than the blink frequency and it is present in the figure 2.1 a).

The opposite effect is illustrated in the figure 2.1 b). If the blink frequency is less than the rotation frequency, the first flash will illuminate the mark in one position, but the

second flash will illuminate the mark in a forward position, and so on because the rotation frequency is faster than the blink frequency. The figure 2.1 c) presents the stationary effect, which happens when the blink frequency is equal to the rotation frequency, so the flashes always illuminate the mark in the same position causing identical images.

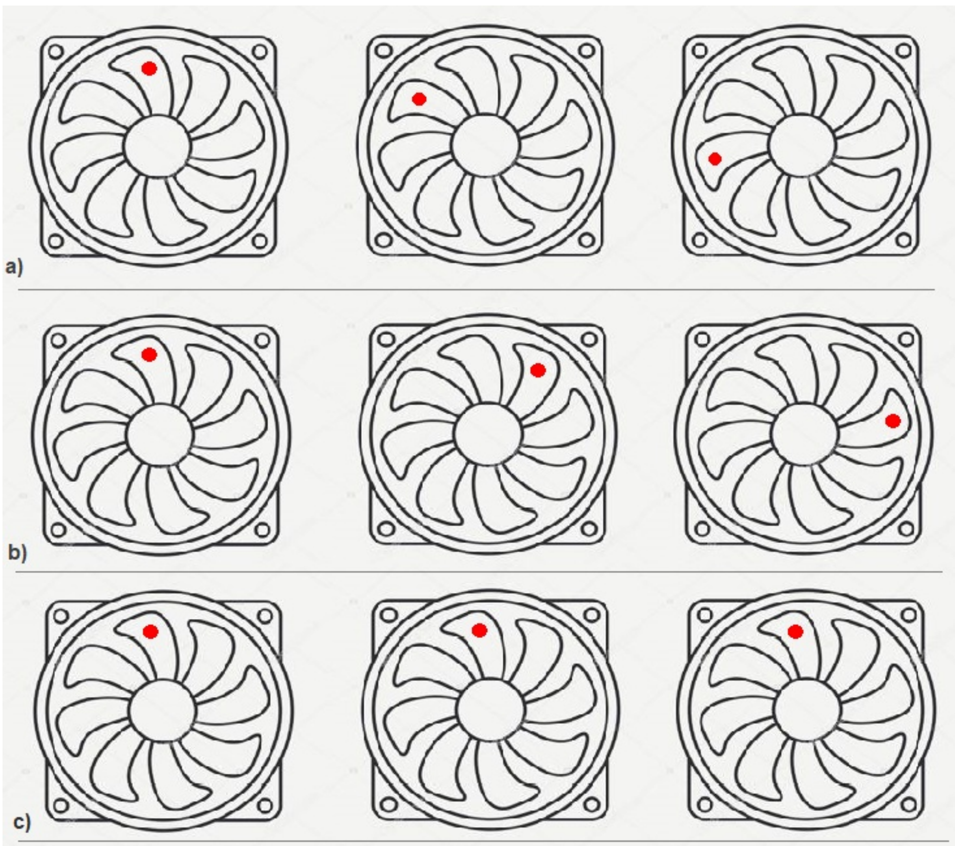


Figure 2.1: Stroboscopic effect illustration.

Therefore, this exhibition of slow-motion provided by stroboscopic effect is useful to determine the angular velocity and analyze irregularities in machines with high velocity, because many times the problems can't be seen by the human eyes or the contact with the machine is very difficult and dangerous [2]. It's important to highlight the care that should be taken with this phenomenon, because depending on the situation, some moving parts can be seen as being stopped, of an undesirable way, causing accidents [10].

The stationary visualization of a rotate movement can also be observed if the flashes velocity are multiples or submultiples of the rotation velocity. In those cases, the motion

will also appears to be stopped, but the difference will be the amount of marks that will be seen. The figure 2.2 illustrates how the stationary images are seen in these situations [2].

Considering one mark on the rotating machine, if the both frequencies are equal, just one mark is seen on the stationary image, and this frequency is called fundamental frequency. If the flashing rate is twice the fundamental velocity of the machine, or also called second harmonic, two marks will be seen in a distance of 180 degrees. If the flashing rate is three times the fundamental velocity of the machine, third harmonic, three marks will be seen in a distance of 120 degrees and so on [2].

Then, if the light blinks at twice the object's rotation velocity, when it is halfway through its rotation another flash of light will illuminate it causing the effect of two marks. For this reason, to avoid errors measurements, it is recommended to start the velocity measurements at a high flash rate or the instrument's maximum flash rate, and then slow down until only one mark is seen [2].

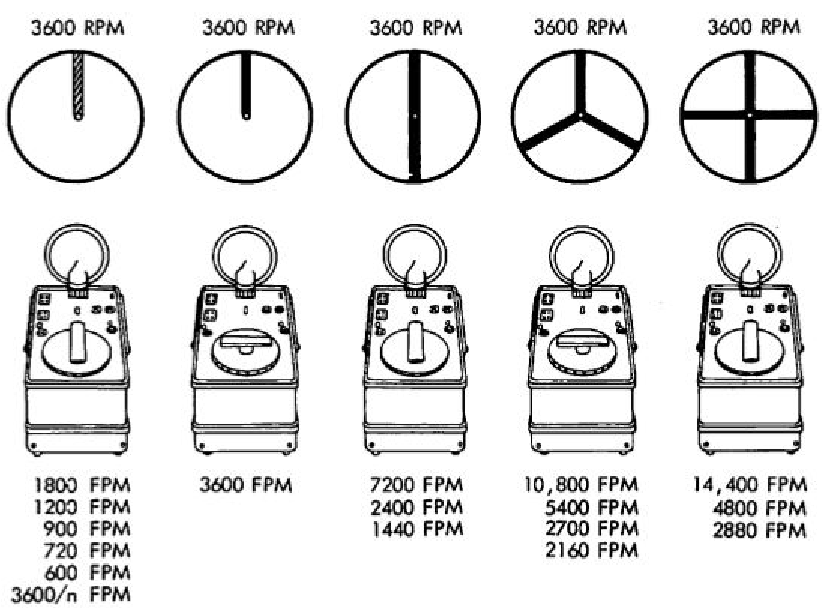


Figure 2.2: Stationary images of the stroboscopic effect caused by harmonic and subharmonic flashing rates [2].

2.2 Stroboscope: the physical device

A stroboscope is an instrument applied to observe the stroboscopic effect, consisting, basically, of a lamp and an electronic circuit. The lamp is responsible for illuminating, in different frequencies, the moving object, which should contain a mark as a reference point, and the electronic circuit able to control the frequencies of light flashes. Usually, feeding is by the use of batteries.

This device allows analyzing and determining the angular velocity of rotational movements through the synchronization between the movement frequency and pulse light frequency, generating an illusion of stopped motion. With this instrument, there is the possibility to do measurement without mechanical contact with the moving object, representing an advantage regarding traditional measurement methods [13].

The name "stroboscope" arose from the junction of two Greek words, meaning "whirling watcher" [2], this meaning seems strange, but this is because the first stroboscopes that emerged were different from the current ones. In 1832, the Australian Simon Von Stampfer created the first stroboscope for animation cartoon purposes, this device was an only disc with a sequence of painted images and when the disc was turned, the image movements appeared [14].

The first stroboscopes were mechanical and followed the same principle of the discs, which had slots with equal intervals and through them, the human eyes could look the movement with interrupts referring the equal intervals [2]. Later, in 1931, an electrical engineer called Harold Edgerton gave rise to an electronic stroboscope [14], presented in figure 2.3. According to [2] this device produced an intense and brief flash through a mercury-vapor tube, which discharged a capacitor.

In [2] is cited some advantages of the electronic stroboscope over the mechanical, present below:

> "The effective illumination on the object was increased; the flash duration was shortened to a few microseconds; the flashing rate could be easily and precisely adjusted and accurately calibrate; several observers could view the

object simultaneously. (A rotating disk or a mechanical shutter could accommodate only one observer at a time.)" [2]

Figure 2.3: First electronic stroboscope [2].

The modern electronic stroboscopes are similar to figure 2.4, including a LED source to illuminate the moving object and a voltage pulse generator [7], responsible for controlling the frequency of light flashes. The frequencies can be adjusted by the user through buttons until the stroboscope effect is observed, that is, until the object appears stopped. The current stroboscopes also include a display, where the information is shown, usually this information is the angular velocity in Rotations Per Minute (RPM).

Figure 2.4: Example of a modern electronic stroboscope [15].

The voltage pulse generator consists to generate a square waveform, with a period that can be changed but the duty cycle, that is, the light pulse duration or the time that the signal has been active, must be short and invariable. It is illustrated in figure 2.5.

According to [12], the duty cycle must be below 10% of the total period [10], for the better visualization of frozen motion by the human eyes without blur. However, must pay attention, because a too-short pulse duration may affect the image to be observed, resulting in small brightness [7].

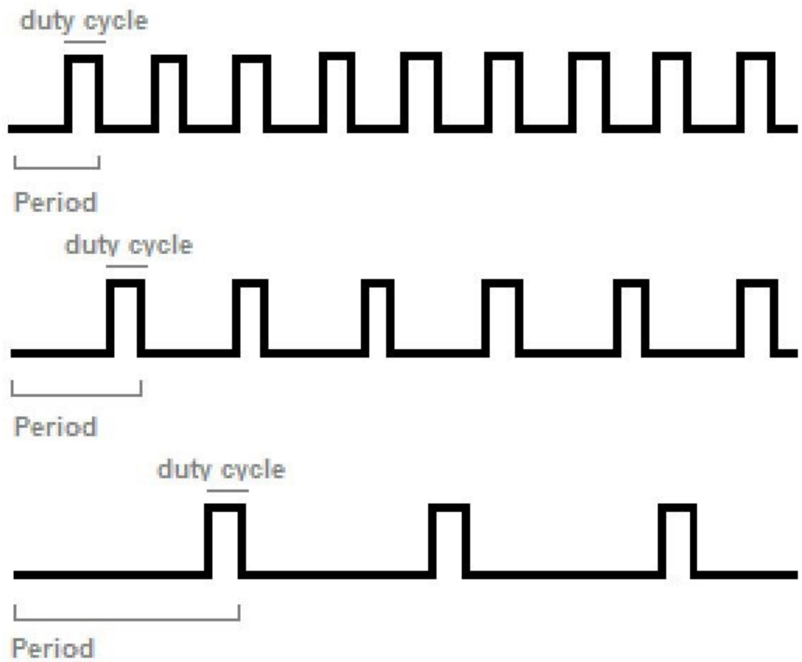


Figure 2.5: Square waveform with variable period and fixed duty cycle.

The stroboscopic effect that occur with a frequency ranging from 2 to 55 Hz, can affect some watchers causing photosensitive seizures, therefore the duration for observation of stroboscopic effects are limited to half a minute or less by work safety regulations [13].

2.2.1 Applications

The stroboscope applications cover many areas, including industry, education, medicine, movies, party illumination and optical illusion. In the industry the stroboscope is commonly applied as a measurement instrument, monitoring operation and determining the velocity and frequency of rotational machines without physical contact. Also used in inspections and quality assessment of propellers, motors, shafts, gears, pulleys, chains,

sprockets, textile processes, in terms of balancing, slip and vibration measurement. In addition to assisting in the identification and troubleshooting of high-speed machines, because it provides slow-motion visualization of the movement [16], [17].

This device can also be applied in the measurement of bullet speed, torque measurement, investigation of loudspeaker operation through oscillation analysis, lead shot manufacturing inspection, because in the fabrication process there is the solidification of molten lead in free fall, allowing the observation the size and shape of the pellets [13]. It can also be applied to television frequency measurement, fluorescent tubes, and light bulbs [18], [19].

On education, the stroboscope is useful to learn and to demonstrate the stroboscopic effect in the physics study and mechanical experiments , observation of object trajectories and acceleration of freely falling bodies through the use of stroboscopic photographs [3], [7], [9], [20], [21], expanding classroom learning. In medicine the stroboscopic effect is applied in the area of laryngology, assisting in diagnosis of vocal cord problems, through the study of the vocal cord vibration [10], [14]. In [22] the stroboscope is applied to excite fluorophores, as an illumination system for fluorescence microscopy.

The stroboscope is also applied in decorative illumination at parties and along with photographs as a means of artistic expression. Besides that, the stroboscopic effect can be found in movies because it consists of joining several successively displayed images with a constant velocity. The effect can be observed, as an instance, in situations where car wheels or airplane propellers appear to be rotating in the opposite direction, this is because the frequency of rotation of these equipment is independent of frequency at which images are displayed [10].

2.2.2 Analysis of existing commercial solutions

Performing research about the stroboscopes commercially available nowadays, it could be found diverse industries that manufacture stroboscopes of many types. Basically, there

are the portable or also called stroboscope hand-held, the more compact called pocket-stroboscope, the fixed and some for specific applications, like those applied to illuminate parties [23].

Currently, most of the stroboscopes are digital and are manufactured using LED technology, but one still can be found the analog models. There are also found stroboscopes with xenon lamps, with built-in tachometers and those with high-intensity. In some device catalogs there is a recommended distance to the object of 20-50 cm, the most stroboscopes found are powered by AA, Li-Ion or rechargeable batteries and all of them have a cold color temperature, around 6000K [23].

The compact stroboscopes or pocket-stroboscopes are small, rugged, lightweight, practical to put in pockets and use with one hand. Figure 2.6 shows an example of an LED pocket-stroboscope manufactured by Monarch Instruments, which has 7 LED array, reaching the maximum of 8300 Lux, with an adjustable flash duration from 0.5 to 2500us and a measurement rate from 30 to 300000 RPM [24].

Figure 2.6: PLS Pocket LED Stroboscope [24].

The pocket-stroboscopes have a measurement rate ranging from 30 to 300000 RPM, depending on the model the maximum limit may be lower. The illuminance, that is, the intensity of illumination received by a surface [25] depends on the number and the kind of lamps applied, reaching until 3800 Lux, as the HELIO-STROB micro2, manufactured by Elmed Messtechnik, shown in figure 2.7, which uses 3 ultra-bright LEDs, with a flash duration of 20us and a measurement rate from 60 to 99999 RPM [26].

Figure 2.7: HELIO-STROB micro2 [26].

Another example is the PCE-LES 300 manufactured by PCE Instruments, shown in figure 2.8, a high-intensity compact stroboscope, which includes 9 high power LEDs, reaching 5100 Lux at 6000 RPM at 20 cm of distance, with a measurement rate up to 120000 RPM [23]. According to sales websites and manufacturers, the prices for these compact devices ranging from €200 to €1000, depending on the model and the technology used.

Figure 2.8: PCE-LES 300 [23].

The portable stroboscopes or strobe hand-held, which use the LED technology are similar in design to figure 2.9, the Nova-Strobe LED manufactured by Monarch Instruments, with a measurement rate that ranges from 30 RPM to 500000 RPM and it has 12 LEDs, reaching a maximum light output of up to 27000 Lux [24]. According to sales websites and manufacturers, the price for these stroboscopes models range from €200 to €2000, most around €1000 [27]–[31].

Figure 2.9: Nova-Strobe LED [23].

The stroboscopes that use Xenon lamps, like in figure 2.10, which is the Model DT-311N manufactured by Schmidt Control Instruments, has the measurement rate ranging from 30 RPM to 35000 RPM, with an illuminance of approximately 3000 Lux, a flash duration of 10-40 us [32] and the prices are similar to the LED stroboscopes. Xenon lamps became less used, due to the advantages of LED technology, such as low energy consumption and low cost [29].

Figure 2.10: Xenon stroboscope hand-held Model DT-311N [23].

There are also available in the market the high intensity LED stroboscopes, which include a large number of LEDs, ranging from 40 to 118 LEDs for the devices found. The measurement rate for all of them goes up to 300000 RPM and the prices are above 2000 euros. The SKF TKRS 41 manufactured by SKF, presented in figure 2.11, and the RT strobe Super qbLED manufactured by Rheintacho, reaches until 8000 Lux at 6000 RPM with a distance of 30cm [33].

It is also found on the market the fixed stroboscopes, as presented in figure 2.12, called Stroboscope RT STROBE 7000 LED, manufactured by Rheintacho, a device fixed and

Figure 2.11: High intensity LED stroboscope hand-held SKF TKRS 41 [33].

with high light intensity, including 7000 LEDs and a cost above €3000. This tool has a measurement rate up to 120000 RPM, reaching 9000 Lux at 30cm, the flash duration is adjustable, varying from 1 to 1000us and the voltage supply is 24V DC [34]. On the Rheintacho website, there also exists stroboscopes similar to these, but using Xenon lamps and with a lower light intensity than LED lamps.

Figure 2.12: Stroboscope RT STROBE 7000 [35].

2.3 Calibration

The calibration is the procedure applied to ensure that a device is working correctly and providing accurate measurements [36]. The instrument's calibration should be done frequently because of the aging of electronic components, temperature, and changes in power influence in the performance and accuracy of measurements. The ideal is to realize it before every velocity measurement [2].

The stroboscope calibration can be done using a rotating equipment with a mark,

which its velocity is known. Adjusting the stroboscope frequencies, it is possible to find the moment when the movement appears to be stopped and then compare the known motor velocity to what the stroboscope displays.

In [37] the calibration of a speed transducer is done through the measurement of the motor velocity with a precision tachometer and the frequency of the output signal with an oscilloscope. Through the plotting a graph, it was established a relation between frequency of the output signal and motor velocity measured by the tachometer.

Another way of calibration is through the use of another circuit, presented in [9], composed of a Light Dependent Resistor (LDR), a light sensor that varies its resistance according to the light intensity, a resistor in series and powered by a Direct Current (DC) source. This sensor is put in front of the stroboscope lamp and through the use of an oscilloscope, it's possible view the resistance variations and calculates the time between them, which refers to the time between flashes and consequently get the frequency.

2.4 Prototyping in 3d printing

The devices prototyping includes the creation of a design, which can be obtained through the use of 3D printing that, according to [38], can be considered a technological revolution, it has gained the attention and interest of industries and research laboratories because this tool enables infinite possibilities [6] to design objects quickly and easily and creating physical prototypes with accuracy and precision [39].

This concept was developed by Charles Hull, a physics engineer from the University of Colorado. In the beginning 1980s, he started to work on developing plastic devices and established 3D Systems in 1986, creating the STL file format from CAD software. The first 3D printer, called "Stereolithography Apparatus", was developed by Hull and 3D Systems and posteriorly the first commercial 3D printer, the SLA-250. With his work, 3D printing leveraged the development and creation of physical objects [39].

3D printing is a technology applied to create three-dimensional objects through the successive deposition of layers of material and this is controlled digitally. This process

is also called additive manufacturing, because objects are created adding, rather than removing material, like happened in subtractive manufacturing. The last one is usually applied for objects based on metal or wood, while the additive process is more used to create objects based on plastic [6].

Regarding rapid prototyping, both techniques are valid, but many other factors should be considered, as the complexity of the objects, material, cost, and the number of replicates. The main difference is in relation to complex design with hollow parts because this kind of object can only be fabricated by additive manufacturing. Besides that, this kind of process reduces energy costs and material waste [6].

Nowadays, there are many kinds of materials that can be used for 3D printing, but the most common is plastic, being ABS, PLA, and Nylon. However, metal, ceramics, wood particles, salt, sugar, and even chocolate have been used for it. The most printers available on the market prints objects through the use of a single type of material, but with the constant advance of technology, there are already printers that print with more than 100 materials, as an instance, the Stratasys Objet500 Connex that costs about 250000 dollars [38].

The first part of the 3D printing process is the creation of a digital geometric model in 3D of the desired object through the utilization of a CAD software, 3D scanner or photogrammetry. After that, it's necessary to convert the file to the STL file format, a universal file format, which has all the information and a list of coordinates about the 3D object model. A 3D printer software converts the STL file data to a G-cod file, which divides the object model into a series of slices, that is, several Two Dimensions (2D) layers and stores geometrical information. With this file, the 3D printer deposits the material layer-by-layer until the 3d object is formed. The figure 2.13 illustrates these steps [6].

There are four categories of the way the 2D layers of the material are deposited. Photopolymerization was the first method created and consisting of the polymer solidification through exposure to UV light, this way solidified layers are successively stacked. The extrusion method makes the deposition of the material from a nozzle head dispenser after

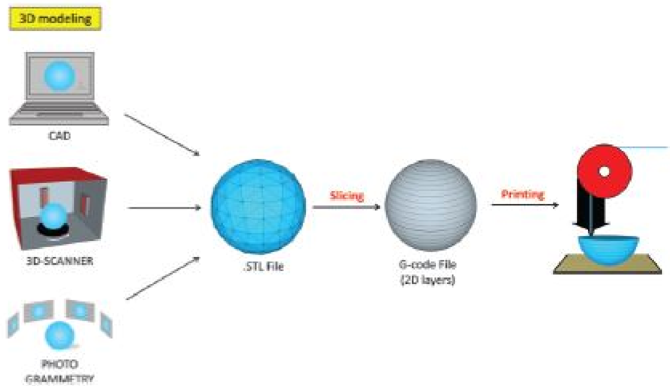


Figure 2.13: 3D printing process [6]

material liquefaction. Technologies very common that use these methods are the Stereolithography Apparatus (SLA) for the first method and the Fused Deposition Modeling (FDM) for the second method, which uses thermoplastic materials [6], [39].

Another method is called powder based and uses powder polymer with particle sizes ranging between 50 and 100 μm. These particles attached through liquid glue or laser beam in the exact positions according to the model. A popular technique that uses this method is known as Selective Laser Sintering (SLS). The last method is defined as lamination or Laminated Object Manufacturing (LOM), which occurs the lamination of materials like a sheet, cut by laser obtaining the contour and later the stacking. [6], [39].

3D printing allows the fabrication of several kinds of objects, for example, prototypes, tools, molds, body parts, prosthetics, toys, musical instruments, art, and even food. The popularization and the constant cost savings of 3D printers have taken them beyond the industry, so that anyone can have their own printer and print what they want. Below are some examples of 3D printing prototyping applications [38].

A 3D prototyping of human aorta is presented in figure 2.14, which is useful for demonstrating and analyzes of the best treatment strategy, besides that, it can assist in patient care, so that he can better understand the pathology. This kind of work has been applied in medical research to create and reproduce 3D models of living organs [40].

Figure 2.15 presents two examples of multifunctional devices created by 3D printing. The figure 2.15 a) shows a game dice, which includes a processor, an accelerometer, and

LEDs to illuminate the upper face of the die, making the game more modern, attractive and different. The figure 2.15 b) illustrates a periodic spiral antenna, which enables dielectrics with different geometries providing new levels of performance [41].

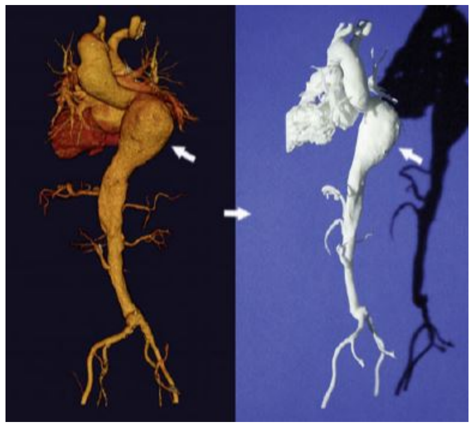


Figure 2.14: 3D prototyping of human aorta [40]

a) b)

Figure 2.15: a) Game dice b) Periodic spiral antenna [41]

A toy character with a heart embedded inside, is shown in figure 2.16 a). The heart includes hollow and closed air tubes, which were printed vertically like cylinders and are illuminated with a LED [42]. In figure 2.16 b) it is presented a capacitive touch sensor, which has submerged wire mesh inside thermoplastic structures in 3D printed, acting as a capacitive plate [41].

3D printing can also be useful in education with the creation of structures and models, which helps the students to understand and to see better about specific issues. Educational

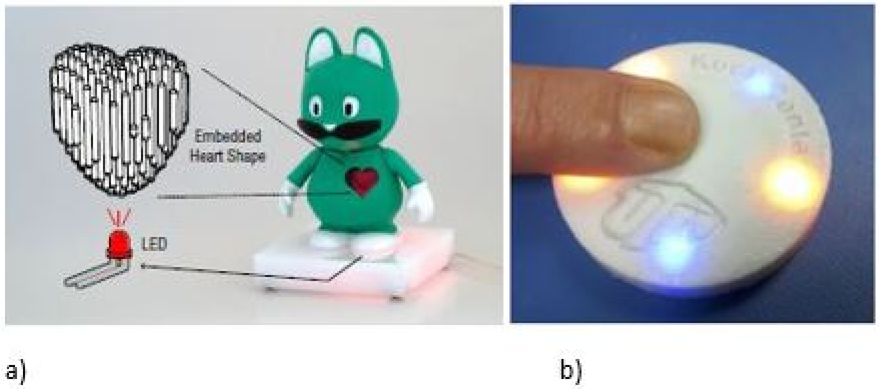


Figure 2.16: a) 3D printed toy character b) 3D printed capacitive touch sensor [42] [41]

applications of 3D printing go from anatomic models from medicine to robots and physical devices for technology and engineering education [39].

2.5 STEAM education

As explained in previous sections, the stroboscope can be applied not only in industry but in other areas, as an instance, the education, assisting the teaching of physics, mechatronics and technology. A new study metodology, called STEAM, has been widely applied around the world, including schools and universities, in order to increase students' interest in areas as science, technology, engineering, arts and mathematics.

In 2001, Judith A. Ramaley of the National Science Foundation created the concept of STEM, which includes science, technology, engineering and math in a study methodology, which has the object to encourage the students to learn these concepts in a structured way. Activities based on the STEM methodology makes students develop skills to solve quotidian problems with critical thinking and draw their own conclusions [8].

STEM doesn't follow the education traditional model because the disciplines have a focus on projects, this way, the students learn scientific knowledge and how they can apply it in real projects. However, depending on the situation, these projects don't involve only STEM concepts, but ideas like design elements and forms. For this reason, the art was included in the STEM, becoming STEAM, which represents STEM plus art [8].

Through the implementation of STEAM education in school's curriculum, the students are encouragement to develop solutions, apply their knowledge, work in team and explore real-world problems [8], preparing them for the professional future, helping them to understand the relevance to create a product or develop a work that meets the needs of society and human. Besides that, the students can discover an interest or not in engineering or arts courses [43].

In the last decade, studies reveal a decrease of students that has an interest in engineering areas in contrast to the current market need for science, technology, engineering and mathematics professionals. Several countries see the importance of uniting education with industry and propose a policy for both to work together, which aids the development of the economy and increases the number of interested and appropriate people [43], [44].

Attracting students to pursue careers related to STEAM represents an advantage for the economy and society [44]. The use of this methodology at schools allows linking high school students to university courses, where they will apply their knowledge through engineering or scientific research [43]. Many programs and courses related to STEAM have been applied in several schools and even universities all around the world [45].

An outreach program that happened at a public middle school in Brooklyn, NY, USA, had the objective to encourage student's interest in subjects like mechatronics, biology, math, and mainly engineering. The results showed that students involved in this program have an interest in engineering and pursue careers in STEAM. Besides demonstrate an understanding of the relationship between engineering and nature, unlike students who didn't participate in the program [44].

The use of technology, physical devices, and interactive objects in education has played an important role in arousing interest and curiosity in students [44]. Nowadays, the mechatronics and robotics fields are the most popular and promising for the industry. So, these subjects have been widely used in education, universities and training processes to motivate workers and students [46].

According to [47] electrical and mechanical systems can be useful to teach control theory, programming, electronics, and mechanics, and destroy the view that these subjects

are only for advanced undergraduates and helping high school students understand the importance of these topics in building complex systems.

Therefore, physical devices like the stroboscope, can help high school students to understand better physics concepts, even as introduce topics about technology, electronics, mechanics, programming and engineering, spreading STEAM concepts. Through the use of this prototype at the classes, they can learn theoretic knowledge about electronics, microcontrollers, programming, and then understand how all concepts together create such important equipment for the industry and see how it works in practice.

This instrument can also be useful for graduate courses in the universities auxiliary scientific research. According to [46], education in engineering needs to teach theoretical knowledge as well as practical experiences. It's important have traditional techniques, like homework, but this is not enough for student mastery. Then, the creation of education tools is very important to help graduate students developing their experience and this point have been attracted much attention of educators.

Chapter 3

Methodology

This chapter presents a description of the problem and the proposed solution. It presents in detail the materials, tools, concepts and methods applied for the solution development, such as the tasks that the system must perform. At the end of the chapter, it is explained how the calibration and validation tests were elaborated.

Aiming the relevance of the stroboscope in measurement processes at the industry, preventive maintenance, the aid in the study of movements, teaching physics and its high cost, it is proposed in this work to develop a low-cost stroboscope, with performance close to the stroboscopes already available in the market.

As presented in section 2.2, the most modern stroboscopes are digital, with LED technology, including buttons, displays and allowing the precise adjustment. The device must be capable of generating light flashes at different frequencies, which are set by the user using buttons and showing their velocities on a display.

For the stroboscope development, it is necessary an electronic part, including a microcontroller able to process the buttons information to generate a modulated signal at different frequencies responsible for blinking the LEDs, and able to show the angular velocity in RPM on the display. It is also needed a mechanical part, related to device design and structure. In addition to the calibration and validation processes, to ensure accurate measurements.

3.1 Electronic part

For the electronic part development, it was chosen the Arduino platform, due to laboratory availability, also because it is open source, has easy to use hardware and software, flexible, accessible, low-cost and has been used in many projects involving electronics and robotics.

The Arduino Uno board, as presented in figure 3.1 contains a 8-bit ATMEGA328P microcontroller, input and output pins, being 14 digital pins and 6 analog pins, LEDs, power supply plugs, 16 MHz crystal oscillator and a 5V voltage regulator. The microcontroller is responsible for all processing and logic of the stroboscope. The programming language is C, which can be programmed through the Arduino Integrated Development Environment (IDE) and where the firmware is developed [5].

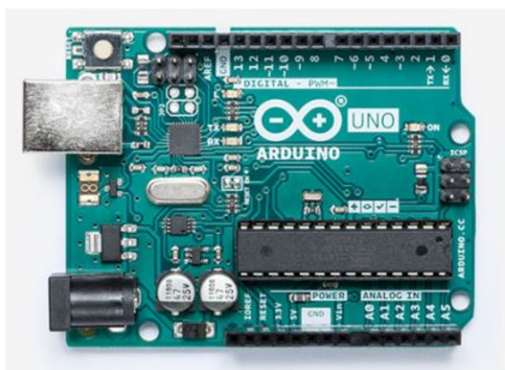


Figure 3.1: Arduino Uno Rev3 [5]

Shields are auxiliary boards, which can be connected over the Arduino board to provide extra features [5]. The advantage of shields is practicality, because the Arduino and the Shield become a single element, gaining more space without the use of extra wires. The Liquid Crystal Display (LCD) Keypad Shield, presented in figure 3.2, was chosen because it has 6 buttons to be the system input, and all of them are connected to analog port A0 of the Arduino, presenting a ports economy. Besides that, this shield has an Alphanumeric LCD Display, where the information is shown.

The light flashes were generated via LEDs SMD5730, presented in figure 3.3, available in the laboratory. These LEDs are low-cost with power around 500mW, color temperature around 6000-6500 Kelvin [48], a luminous intensity of 57 lumens each and through them

it is possible to generate more or fewer lumens depending on the number of LEDs, being lumens the unit of measurement that specifies the amount of light emitted by a lamp.

Figure 3.2: LCD Keypad Shield [49]

Figure 3.3: LED SMD5730 [48]

For the creation of stroboscopic light, it was used 10 LEDs SMD5730, which work with a current of 150mA and a voltage between 2.8V and 3.5V [48]. However, the Arduino Uno that includes the ATMEGA328P microcontroller provides a current of only 40mA and a voltage of 5V on your ports. For this reason, it was needed another electronic circuit that includes other power supply that usually is 12V, the LEDs, resistors for current limitation and a Metal–oxide–semiconductor field-effect transistor (MOSFET) to operate like a valve to turn on and turn off the LEDs when necessary.

The power bank Eurotech, presented in figure 3.4, was chosen to operate as the power supply of the system because it is ergonomic and it has a favorable structure, which can be used as the part where the user holds the stroboscope. Another point is the ease of

loading via the Micro Universal Serial Bus (USB) port, besides that, it has four LEDs battery level indicators.

This power bank, has a power of 10400mAh, Lithium-Ion battery (Li-Ion) and 2 USB outputs, one with a current of 1A and the other with a current of 2.1A. Both outputs have a voltage of 5V, which is sufficient to power the Arduino, but not the driver circuit. Therefore, it was necessary to use a boost converter, a DC/DC converter, which raises the input voltage to the output as the current decreases.

Figure 3.4: Power Bank Eurotech [50]

The figure 3.5 shows the boost converter or step-up converter MT3608, which was chosen for availability in the laboratory and for meeting all needs. This step-up has an input voltage ranging from 2V to 24V and reaching a maximum output of up to 28V [51]. The desired output is adjusted by means of a potentiometer.

Figure 3.5: Boost converter MT3608 [51]

The figure 3.6 illustrates the system operation, which the buttons of LCD Keypad Shield are the inputs of the Arduino board and the microcontroller must interpret the press of the buttons that indicate increasing or decreasing the velocity of light flashes.

Based on that, 2 outputs are generated by the Arduino board, the signal to driver circuit blink the LEDs in the desired velocity and the presentation of the velocity information on the Alphanumeric LCD Display.

Blinking the LEDs at different desired frequencies requires a signal modulation where the frequency is varied and consequently the signal period also varies. As explained in previous chapter, for the visualization of the stroboscopic effect, this signal must be like specified in figure 2.5, with a fixed duty cycle and a period that varies according to the button press.

Therefore, the microcontroller sends the modulated signal to driver circuit, which is responsible for blinking the LEDs in the signal frequency. The power bank's output of 1A powers the Arduino board, where the shield is connected and therefore is also powered. The other power bank's output, of 2.1A, powers the boost converter, which raises the voltage to power the driver circuit of the LEDs.

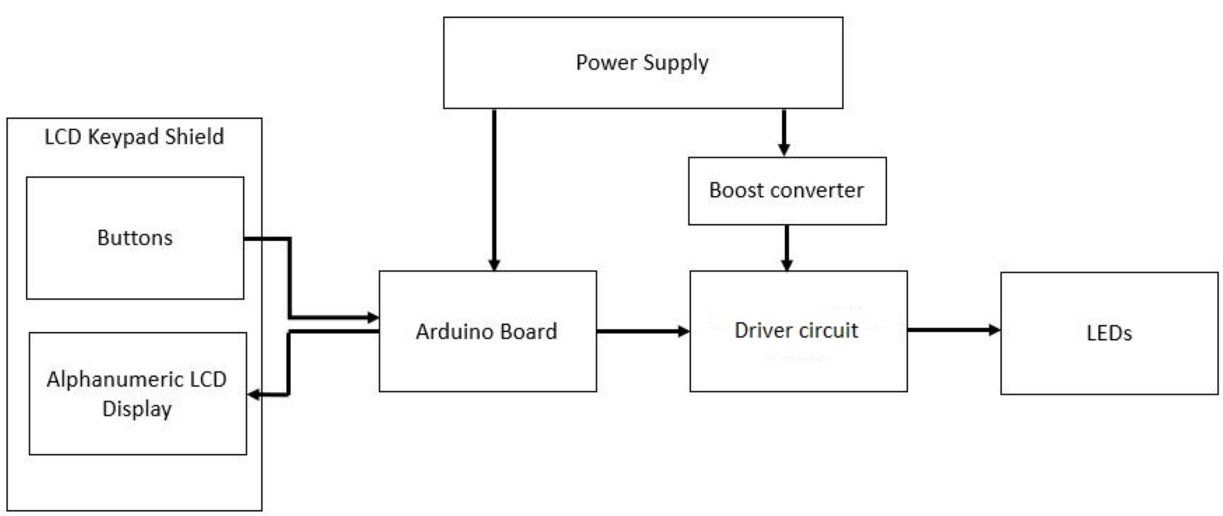


Figure 3.6: System block diagram

3.2 Mechanical design

For the creation of the mechanical design, firstly it was made a 3D drawing, that is, virtual model of the stroboscope structure using the SolidWorks, a 3D CAD software, which was chosen by experience and familiarity. The design of the device was based on the commercial stroboscopes, taking into consideration enough space to arrange all components inside it.

Posteriorly, a 3D printer, showed in figure 3.7, was used to print the 3D object. The prototyping of the device using 3D printing was chosen for the availability of a printer in the laboratory and its practicality, speed and cheap process to create plastic structures. The material used to print was the Polylactic Acid (PLA), a thermoplastic synthetic polymer commonly applied in 3D prints.

Figure 3.7: 3D printer

3.3 Calibration and validation

The calibration of the stroboscope was done using an electronic circuit composed by a LDR luminosity sensor, which should be directed towards the LEDs and through an oscilloscope it is captured the pulses generated by the sensor referring each flash of light.

This way, it was possible to measure the frequency of the LEDs response signal and the frequency of the signal sent to them and check the consistency between them.

The validation and performance tests of the stroboscope was done using a three-phase motor controlled in closed-loop, which has a constant velocity, and a tachometer available on the laboratory, both presented in figure 3.8. It was put a mark on the motor to view the stroboscope effect and then, the three-phase motor was driven in different velocities, which was checked using the tachometer and compared with the stroboscope result.

Figure 3.8: a) Three-phase motor and b) tachometer for tests.

The tachometer is a device also used to measure the number of rotates of an object in RPM. The model in figure 3.8 has two modes, optical tachometer, that is, without contact with the rotate machine, and with the contact. The optical tachometer is composed of a transmitter, generating infrared radiation and a receptor, detecting the infrared radiation, usually through the use of a phototransistor, so it is possible to calculate the time interval between each rotation. For the measurement, the instrument should be close to the surface machine, which needs to have a mark to the infrared return to the receptor and then the velocity is shown on the display [52].

Chapter 4

Development

This chapter describes the steps to develop the stroboscope in order to get the desired features, presenting the applied techniques, difficulties found and solutions to solve such problems. This project was done in the Control, Automation and Robotics Laboratory (LCAR) located in the Polytechnic Institute of Bragança. Firstly, it is presented the work to create the electronics part, including the firmware develop to perform the desired functions and the hardware, that is, the simulations, calculations, circuit assembly and creation of the Printed Circuit Board (PCB).

Then, it is presented the work to create the mechanical design, the features taken into consideration to create the structure of the stroboscope, the final result of the printed object and the processes required after printing. It is discussed how the calibration was done to ensure that the stroboscope performs consistent measurements. In the last section of this chapter, a cost analysis is presented, based on research about the prices of the components used in the prototype [53], [54].

4.1 Electronics part of the prototype

4.1.1 Firmware

For the development of the electronics part of the stroboscope, the first step was the creation of the firmware through the Arduino IDE. The code, available in a repository [55], is based on reading the buttons and sending the modulated signal to digital pin 3 at different frequencies set via the buttons. This signal is responsible for blinking the LEDs and the velocity limits range from 60 RPM to 100000 RPM, which were chosen based on values found in commercial stroboscope catalogs.

In appendix A there is a firmware flowchart that presents the main program steps, which will be better explained throughout this section. The reading and detection of the buttons, and the modulated signal generating occur constantly, while a counter is incremented. The variable named as *State* is 1 if the button is not pressed and 2 if the button is pressed, the next button detection only occurs if it is depressed and pressed again.

The LCD Keypad Shield is based on an analog keyboard, when it is attached on the Arduino board, all the buttons are connected to analog port A0 (AD0) and have 5 stage voltage divider, as show the figure 4.1, then the pressing of each button is identified through values generated in AD0. Therefore, after the program detects a variation in the analog port, indicating that some button was pressed, it is necessary to find which button was pressed.

The values in the AD0 are determined as follows, the Arduino analog/digital converter is 10 bits, so it counts until 1023 with a resolution of $4.9m$V per unity. Then, the converter maps voltages between 0V and 5V, Arduino voltage operation, to integers values between 0 and 1023, being 5V equivalent to 1023. Through the values of the resistors shown in image 4.1 and the voltage divider equation, as presented in equation 4.1, it is possible to find the voltages in AD0 depending to the button pressed, and then convert this voltage to values between 0 and 1023, as in equation 4.2. These equations present the calculations just for the UP button because for the other buttons is the same process [56].

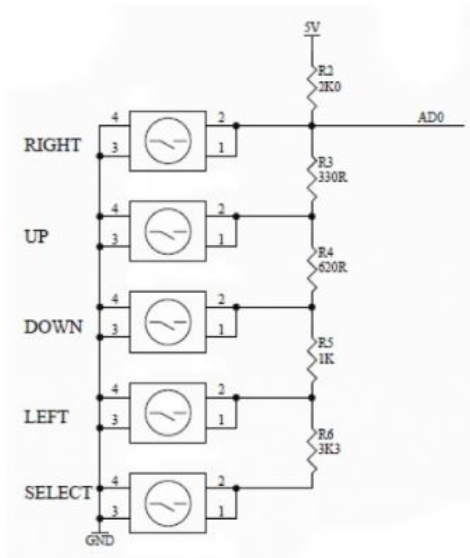


Figure 4.1: LCD Keypad Shield buttons schematic [57].

Therefore, if the RIGHT button is pressed, the value in AD0 is practically 0, because AD0 is connected to the ground. If the UP, DOWN, LEFT or SELECT button is pressed, the value in AD0 can be around 144.89, 329.44, 505.02 or 740.70, respectively. So, for the reading condition of each button the limits chosen were values less than 60, 200, 400, 600, and 800 for right, up, down, left and select buttons, respectively. Each condition can be better visualized in source code available in the repository [55].

$$\begin{aligned} V_{AD0} &= \frac{330\Omega}{(330\Omega+2000\Omega)}.5V \\ V_{AD0} &= 0.708V \end{aligned} \tag{4.1}$$

$$\begin{aligned} ConvertValue &= \frac{V_{AD0}.1023}{5V} \\ ConvertValue &= 144.89 \end{aligned} \tag{4.2}$$

The shield has 6 buttons, being one of them the reset and three chosen to perform the function of adjustments, increment, and decrement. The other two buttons were intended for multiplication and division by 2, to facilitate the visualization of harmonics. The figure 4.2 illustrates the distribution of the buttons functions in the shield. Within each button reading condition, the program changes the angular velocity, based on the values

incremented or decremented, and shows it in RPM on the display. Then, the program calculates and changes the new frequency, the new period of the signal and the *interval value*, which represents the time at the low logic level of the signal, that is, the total period of the signal less the duty cycle.

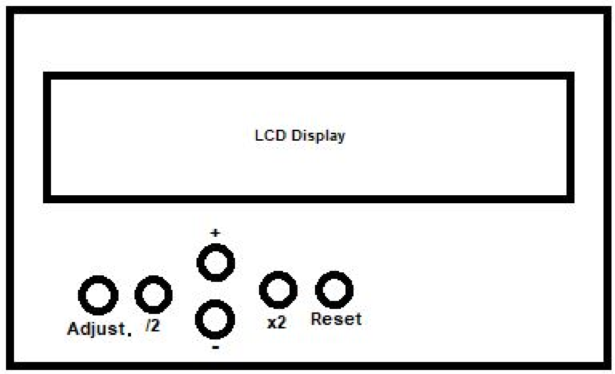


Figure 4.2: Distribution of the buttons functions.

It is important to highlight that the reset and the adjustments buttons don't do changes in the signal period, adjustments just change the value to be incremented or decremented and show the setting on the display. Four settings were chosen to adjust the frequency, being the thick that increments the frequency of 1000Hz in 1000Hz, the medium, fine and ultra-fine, which the increment value is 50Hz, 1Hz and 0.1Hz, respectively.

With the increase in frequency, the signal period tends to decrease and therefore, the value set for the duty cycle can become greater than 10% of the signal period and according to the literature, the duty cycle must be kept around 10% of the period so that the stroboscope effect can be viewed without drag or blur [10], [12]. This way, when the duty cycle is close to overcome 10% of the signal period, it is changed to a value below of that percentage. The duty cycle is constant but not for all velocity values because it is necessary an adjustable duty cycle. In the program, this operation occurs before each change in the signal period.

The last part of the program consists to generate the period of the modulated signal. As a time base, it was used the function *micros()*, which counts the time in microseconds

since the Arduino board start running the program. When this counter reachs the *interval value*, that is, time in low logic level or inactive time, the output signal on digital pin 3 is set in high logic level. As the duty cycle time of the signal is very short, in the microseconds, it was used the function *delayMicroseconds()* to wait the signal active period until it is set in low logic level again, remaining so, until the process is repeated.

This function was only used because it doesn't influence the speed of activation of the button by the user, which is much slower, at the level of milliseconds and no problems were found using it. Other techniques were tested at the firmware, like interruptions, timers and auxiliary variables within state machines, but none was able to generate short enough duty cycles for high speeds, this was only possible with the use of the function *delayMicroseconds()*.

Appendix B presents the images of the modulated digital signal at different frequencies. These figures were taken from the oscilloscope, which was connected to digital pin 3 of the Arduino board, where is the output of the signal. The figure B.1 a) shows the signal at 1000 RPM, that is, about 16.67 Hz and the frequency captured by the oscilloscope was 16.80 Hz with a relative error of 0.08%, representing a small error. The figure B.1 b) shows the signal on a larger scale, where it is possible to see the duty cycle period in 500us, the exact value assigned to this frequency in the firmware.

In figure B.2 a) the signal is in 50000 RPM, that is, about 833.33 Hz, the exact frequency captured by the oscilloscope. For this frequency, the duty cycle period is adjusted to 100us and the figure B.2 b) shows the correct period, being the scale of 250us per division, each interval inside 1 division value 50us and the duty cycle of the signal covers 2 intervals.

The signal in 100000 RPM, presented in figure B.3 a), has a frequency of about 1666,67 Hz and the oscilloscope measured 1506 Hz, representing a relative error of 9.64%, bigger than the errors found previously. The duty cycle period distorted a little to the desired value for this frequency, which is 50us and the oscilloscope captured 60us, as shown in figure B.3 b), presenting a relative error of 20%. However, 60us are still within 10% of the signal period, which would not cause problems in visualizing the stroboscopic effect.

Therefore, according to the relative error increase, a velocity limit was established for the stroboscope prototype, which measures velocities from 60 RPM to 100000 RPM. However, the prototype could not be tested in velocities as high as 100000 RPM, because there isn't a rotating device, available in the laboratory, that works at these velocities.

4.1.2 Hardware

After the development of the firmware, the next step was the development of the hardware. As presented in chapter 3.1, it is necessary to create a driver circuit able to power the LEDs and perform their switching. For that, it was needed electronic components and accomplishing calculations about the resistors' values and transistor conditions, which are described throughout this section.

A MOSFET transistor has 3 terminals as presented in figure 4.3, the gate (G), the source (S) and the drain (D), and according to the voltage at the gate, the current flow between drain and source is controlled. So, the gate must be connected to the digital output port of the Arduino board, where the modulated signal is generated and the LEDs connected to the drain [58].

This electronic component has 3 operation regions, cutting, triode, and saturation. The saturation region is intended if the transistor operates as an amplifier, if it operates as a switch it must work in the cut and triode regions. The MOSFET has to switch the passage or not of the current through the LEDs, allowing them to be turned on and off at different frequencies. This way, it must operate in the triode and cut regions [58].

The transistor used in this project was the IRL540N, which is a type N MOSFET, where the current flows from the collector to the emitter. According to the datasheet, this component has a maximum drain current (I_{Dmax}) of 30A and a drain-to-source breakdown voltage (V_{DS}) of 100V, having a more than sufficient range of values for this application [59].

To ensure that the MOSFET works within triode region, certain conditions must be fulfilled. The only condition to work within cut region is $V_{GS} < V_t$, being the maximum

gate threshold voltage (V_t) of 2V and the voltage between gate and source (V_{GS}) of 5V, that is, the output voltage of the Arduino pin. In this case, V_{GS} needs to be less than 2V, what is possible cutting the current and the voltage at the gate, that is, sending no signal to the Arduino port connected to the gate. The equations 4.3 and 4.4 represents the conditions for triode region. The first condition is ensured, since V_{GS}=5V when a signal in high level is sent by Arduino, and for the second condition, the voltage between drain and source (V_{DS}) must to be less than 3V [58] [59].

$$\begin{aligned} V_{GS} &\geq V_t \\ 5V &\geq 2V \end{aligned} \tag{4.3}$$

$$\begin{aligned} V_{DS} &< V_{GS} - V_t \\ V_{DS} &< 5V - 2V \\ V_{DS} &< 3V \end{aligned} \tag{4.4}$$

In total 10 LEDs SMD5730 were used for the stroboscopic light, being 5 pairs of them in parallel. According to the datasheets, the recommended current is 150mA, so the drain current I_D is 750mA. Each LED has a power of 0.5W, so the total power of the stroboscope is 5W. The transistor static drain-to-source resistance (R_{DS}) is 0.053Ω for V_{GS} equal 5V. The equation 4.5 shows that the V_{DS} fulfills the condition specified in the equation 4.4 through Ohm's Law [48] [59].

$$\begin{aligned} V_{DS} &= R_{DS} \,.\, I_D \\ V_{DS} &= 0.053\Omega \,.\, 750mA \\ V_{DS} &= 0.04V \end{aligned} \tag{4.5}$$

Each LED has a forward voltage between 2.8V and 3.5V, choosing an intermediate value of 3V for operation and through Ohm's Law, it is possible to calculate the value of the resistors placed in series with each pair of LEDs as a way of protecting them [48]. These calculations are presented in equation 4.6, being V_{Total} the 12V power supply of the circuit and V_{LEDs} the voltage on the two LEDs in series. The largest and closest

commercial resistor value available in the laboratory was 47Ω.

$$
\begin{aligned}
R &= V \; / \; I \\
R &= (V_{Total} - V_{DS} - V_{LEDs}) \; / \; I \\
R &= (12V - 0.04V - 6V) \; / \; 150mA \\
R &= 5.96V \; / \; 150mA \\
R &= 39.73\Omega
\end{aligned}
\tag{4.6}
$$

The voltage source for the driver circuit is the step-up converter output, as presented on the system block diagram in figure 3.6. According to voltage increase, the current decreases at the same proportion. The input voltage is power bank 5V and it is regulated to 12V in output, being a proportion of 2.4. Knowing the input current provided by power bank is 2.1A, the output current is decreased to 875mA, being enough to feed all the LEDs, which needs 750mA in total, reaching efficiency of about 89% according to the MT3608 datasheet [51].

The image 4.3 shows the driver circuit schematic, which was assembled on *LTspice*, a software destined to circuit creation and simulation. It was put a signal at the gate to simulate the signal that would come out of Arduino. The resistor R_G was put to limit the trigger current at the gate, and the resistor R_{GS} between gate and source was put to avoid that the gate assumes any voltage value due to noise when it stays floating. These resistors' values were empirically chosen.

After the circuit simulation, all the system was tested on the bench, as presented in figure 4.4. The system presented a perform like desired with current and voltage consumption within the calculated limits. Using a multimeter and an oscilloscope, was checked that the LEDs presented a current consumption of 140mA and the drain current was around 700mA. Therefore, when the transistor worked within triode region, the voltage drop was of 3.08V in each LED, 5.67V over the resistor, and V_{DS} was around 0.17V. When the transistor was cut, there wasn't drain current and no voltage between gate and source, so all the system voltage was in V_{DS}.

After the simulation of the electronics part, the next step was the prototyping of the

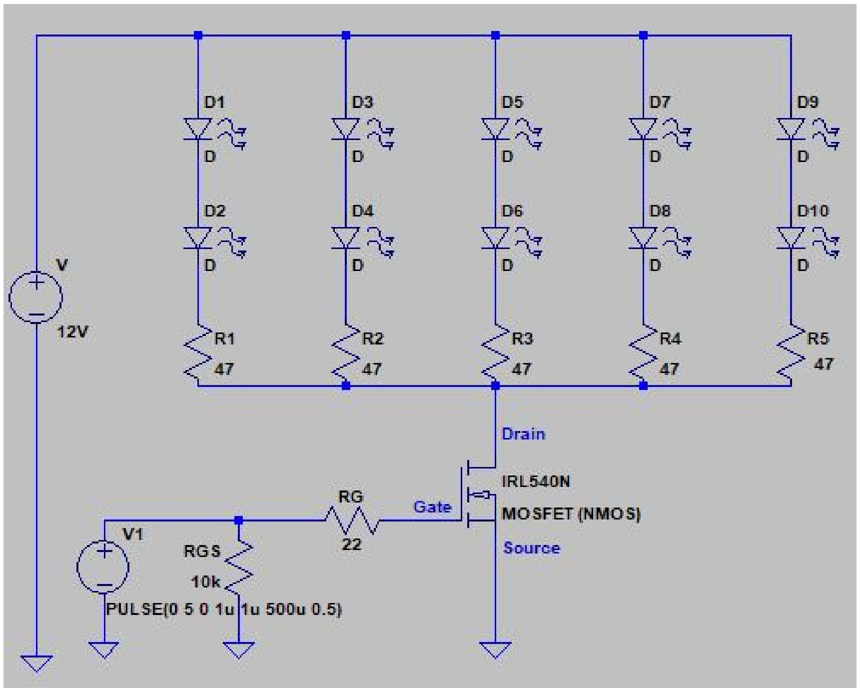


Figure 4.3: Driver circuit.

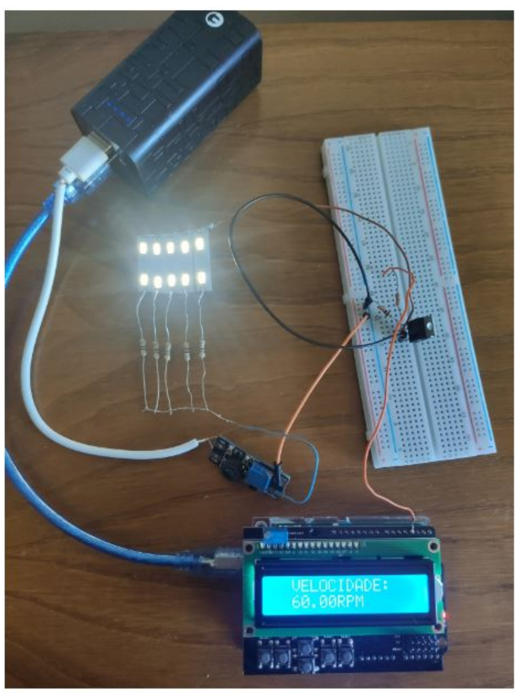


Figure 4.4: Bench tested complete circuit.

PCB, but for that, it was necessary the elaboration of PCB layout, that is, a circuit schematic where are defined the places that the components will attach. The image 4.5 presents the layout created using the *Kicad*, a software that intends to produce circuits, components footprints association and PCB layout elaboration.

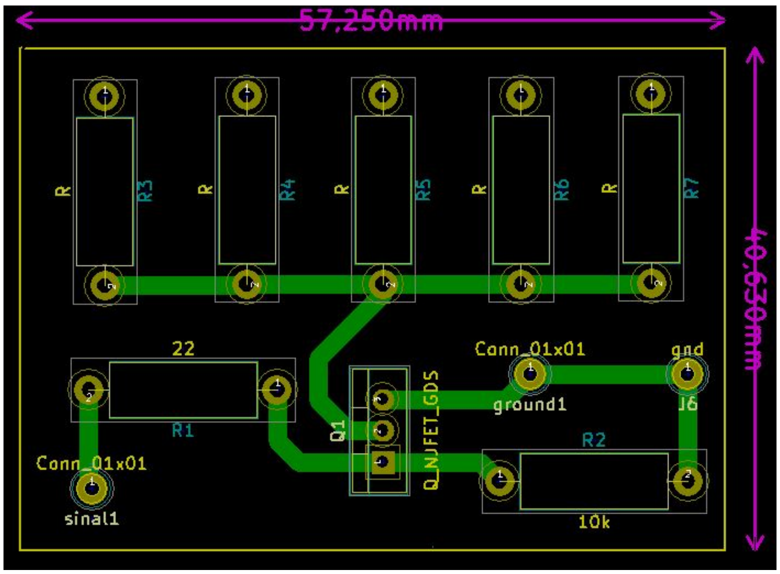


Figure 4.5: PCB layout.

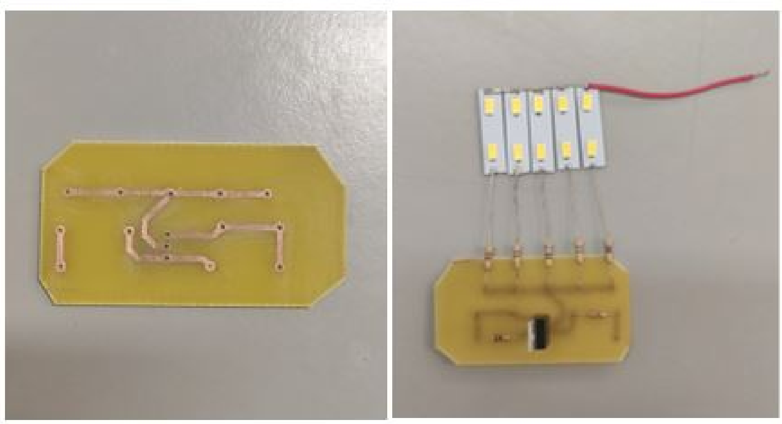
The PCB manufacturing was done manually, so the layout was generated in Portable Document Format (PDF), printed in transfer paper, positioned and fixed on a photosensitive plate, which was inserted into a vacuum chamber, available in the laboratory, where it was exposed to ultraviolet light for a period of 120 seconds. After that, the revelation was done diving the board in a solution containing the revealing, that is, soda solution, and 1 liter of distilled water. This way, the photosensitive ink is removed, keeping only the ink referring to the circuit, as presented in figure 4.6.

With the circuit revealed, the corrosion was done diving the board in an iron perchloride solution, removing all the exposed copper and keeping only the circuit copper, because the photosensitive ink works like a mask, preventing the perchloride corrodes that region. To remove this ink from the tracks, steel wool was rubbed.

The last task consisted to test the tracks connections using a multimeter, drill the board using a drill bench and weld the components using tin and soldering iron, both

available in the laboratory. The figure 4.7 a) shows the PCB after the corrosion and the figure 4.7 b) the PCB with the welded components.

Figure 4.6: PCB revelation process.



a) b)

Figure 4.7: a) Printed circuit board b) Printed circuit board with welded components.

4.2 Mechanical design of the prototype

After all the electronics part concluded, the next step was the creation of the stroboscope design, which was inspired by the portable stroboscopes, as the figure 2.9. The structure was elaborated to be as compact as possible and considering all the electronics components

that would be assembled inside the stroboscope. The figure 4.8 shows the 3D model, in different views, which was drawn on *SolidWorks*.

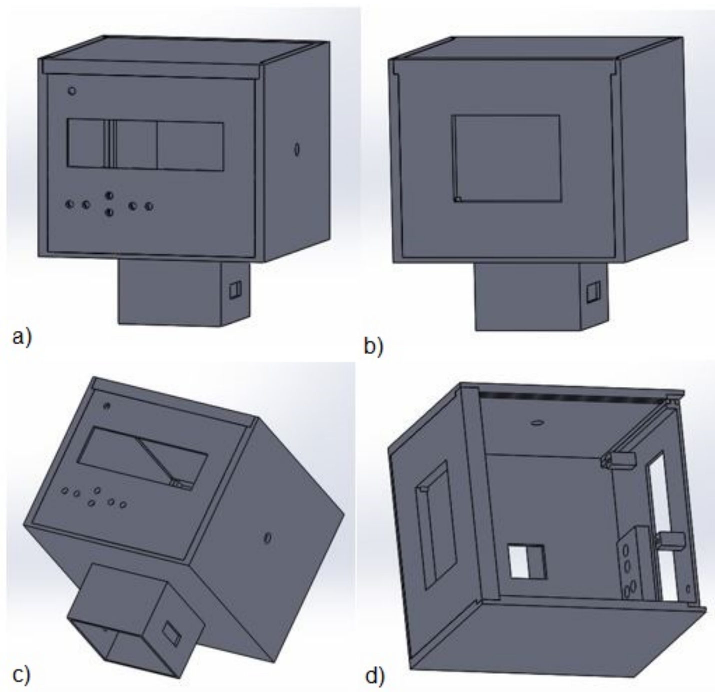


Figure 4.8: 3D drawing of stroboscope design a) front view b) back view c) bottom view d) top view

The figure 4.8 a) represents the front view of the stroboscope, intended to fix the LCD display and the buttons. The figure 4.8 b) shows the back view, where the LEDs are exposed. The figure 4.8 c) corresponds to a bottom view, there is an extension where the power bank is dovetail with the stroboscope structure and this extension has 2 gaps for the battery level visualization and loading. The circular gap on the lateral is intended to turn on/off button of 6 pins, which drives 2 circuits at the same time, the power of the Arduino and the LEDs.

A top view is presented in figure 4.8 d), without the lid, where it is possible to view the space for all the components, including the LCD Keypad Shield, the Arduino board, the driver circuit with the LEDs, the turn on/off button and all connection wires between the components. The dimensions, removing the battery holder, are the height of 82 mm, the width of 97 mm, and the depth of 100 mm.

The six buttons were also drawn on SolidWorks together with support to be dovetailed on the top of them because these buttons would be too short and thin, so this support becomes the external part of the button bigger and comfortable for the pressing. The 3D model files of the button, its support and the other parts of the prototype, are available in a repository [55].

The parts were printed using the 3D printer available in the laboratory, the material used to print was PLA and the total printing time was about 7 hours and 15 minutes. As the plastic available was green and the power bank is black, for appearance purposes, the parts were painted black using a spray appropriate for this material and the result is presented in figure 4.9.

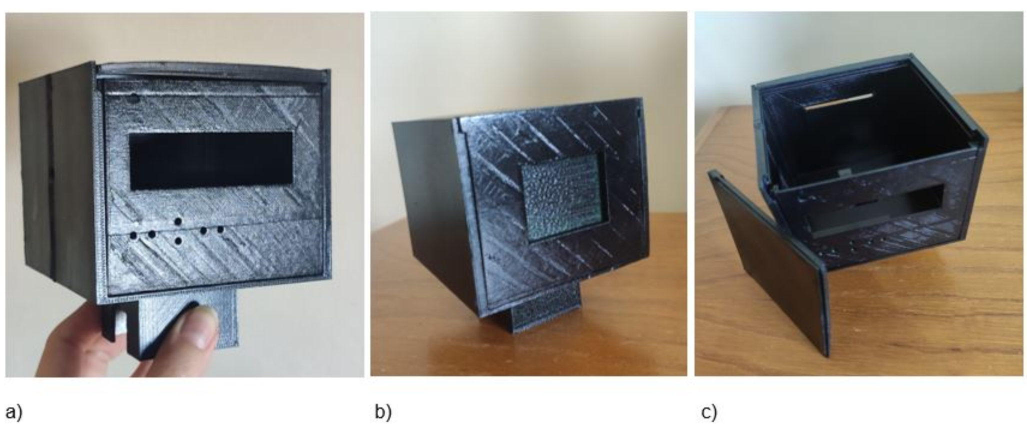


Figure 4.9: Final printed parts a) front view b) back view c) top view

The last task consisted to insert, weld and fix all the electronics components inside the structure, dovetail the buttons, which were kept green, and the power bank, which serves as a support for the user to hold the device. Therefore, the image 4.10 presents the final stroboscope prototype, on the left side is the front view, where it is possible to visualize the LCD display, a gap to control its contrast and the buttons, on the right side of the image 4.10 is the back view, where the LEDs are exposed behind a transparent plastic.

a) b)

Figure 4.10: Final prototype of the stroboscope a) front view b) back view.

4.3 Calibration

The calibration of the stroboscopic light was done using a circuit based on a LDR sensor in series with a 10kΩ resistor, powered by a 5V DC source, and an oscilloscope connected as shows the figure 4.11, to capture the LEDs response signal. The LDR is a luminosity sensor, which varies its resistance according to the intensity of light focused on it.

According to the datasheet, the higher the luminous intensity, the lower the resistance, then every light flash, the LDR resistance decrease, and the resistor voltage increase [60]. The sensor was positioned in front of the stroboscopic light and through the oscilloscope, it was possible to visualize the voltage pulses over the resistor, generated by varying the LDR resistance every flash of light. Then, the frequency of both signals could be compared.

In appendix C are the images captured by the oscilloscope with the stroboscope in different frequencies, where the blue signal represents the LED response signal and the yellow signal represents the modulated signal sent by the Arduino. Through these images

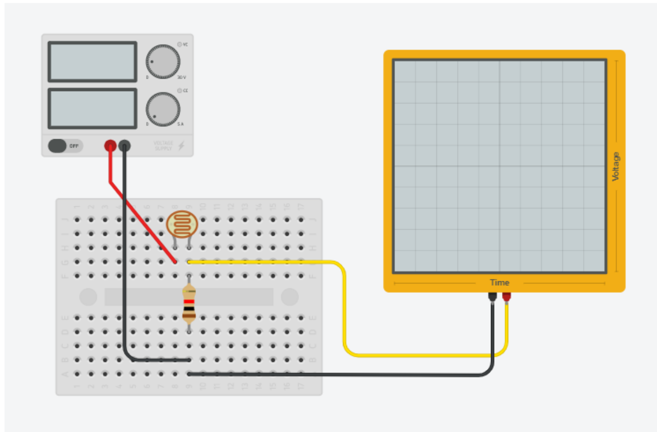


Figure 4.11: Circuit applied to calibrate the stroboscopic light.

it was noticed that the frequencies of both signals coincided with each other, confirming that the LED response was consistent with the signal sent by the microcontroller.

It is possible to observe in figures, that the voltage level of the blue signal didn't return to zero, because it wasn't possible to realize these measurements in a place totally dark, so the LDR always detected a little of luminosity. In figure C.3, at 10000 RPM, the blue signal that represents the LED response, began to distort from the modulated signal. This happened because the LDR response isn't instantaneous, there is a latency time until the sensor answers by the transition from dark to light and vice-versa.

According to the datasheet [61], there is a rise time and a fall time that varies depending on the Lux, the amount of light over a surface. As presented in chapter 3, each LED SMD5730 has 57 lumens, converting this value in Lux with a total of 10 LEDs at a distance of 35cm, the stroboscope has 18144 Lux. Then, the rise time is around 2.8ms and the fall time is around 48ms. At 10000 RPM, the period of the signal is 6ms, so would be necessary more time to the blue signal come back close to a voltage null. Therefore, with the frequency increase and the period decrease, the LDR sensor response becomes more and more constant.

4.4 Cost analysis of the prototype

One of the goals of this project was the development of a low-cost stroboscope, then it was done a search about the components price on Portuguese websites and foreign websites. The table 4.1 presents the costs of each electronic component used to create the hardware of the stroboscope. The 3D printer showed a quantity of 194,5g of PLA plastic used to print the device structure, based on the quantity of PLA sold on the market, the price for the quantity used was estimated.

Table 4.1: Prototype cost analysis table

Components	**Portugal**	**Foreign**
Arduino UNO	€22	€5
LCD Keypad Shield	€9,74	€2
Power bank Eurotech	€19,5	€13,5
Boost converter	€1,8	€0,3
10 LEDs SMD5730	€0,5	€0,2
MOSFET IRL540N	€0,2	€0,2
7 resistors	€0,07	€0,07
Button on/off 6 pins	€2	€1
PLA plastic	€9,73	€3,64
Total Price	**€65,54**	**€25,91**

It is important to highlight that it wasn't found the MOSFET IRL540N component on Portuguese websites, so it was used the same price in foreign. The components price on foreign websites is cheaper than in Portugal. Therefore, through the table above it is possible to notice that the cost to prototype the stroboscope was of €25,91 in foreign and of €65.54 in Portugal, representing more than double the price. Even so, both the costs are cheaper than the stroboscopes available on the market currently with similar features, as presented in chapter 2.2.2.

One way to reduce the prototype cost would be not using the Arduino board, which includes the microcontroller ATMEGA328P and many functions and other components that are not totally used. The solution would be to use just the microcontroller and creating the board itself with only the components that would be used and needed for this project, without using the Arduino board as a whole. Realizing a search on the

Internet, it was found this integrated circuit with a cost of around €6 in Portugal and of €2 in foreign, which would considerably reduce the final price of the prototype.

Chapter 5

Prototype apply in Summer Camp at IPB - A RoboSTEAM activity

In this chapter, it is described the RoboSTEAM Project, its goals and approaches, followed by the description about the Summer Camp, a summer course that took place at IPB, which received several students from secondary schools. This course was part of the RoboSTEAM Project and a stroboscope initial prototype was applied as a way to teach microcontrollers, STEAM concepts, and developing CT, based on a physical device.

5.1 RoboSTEAM Project

Starting from the current need to prepare efficient professionals to solve problems and find the best solutions in an emerging digital society, the concept about STEAM, as presented in section 2.5, has spread to many countries in order to integrate the disciplines that compose it in educational landscape [62] [63].

The RoboSTEAM - Integrating STEAM and Computational Thinking development by using robotics and physical devices - ERASMUS+ Project is a European project co-funded by Erasmus+ KA2-Cooperation and Innovation for Good Practices and Strategic Partnerships for school education. The main goal is the CT development using robots and physical devices, providing tools to assist the teaching in STEAM areas and applying

innovative practices based on CBL approaches [64].

Through two pilots, experiences and challenges between schools in different socioeconomic contexts are implemented. The project consortium is coordinated by the University of Leon and includes the participation of CeDRI / IPB among other 6 partners and the duration is 20 months. Both the pilots took place at Emidio Garcia School from Bragança - Portugal and were based on a CBL approach, being an activity of the RoboSTEAM Project [64].

According to [62], [64] CBL is a teaching methodology intended to encourage students to solve real-world problems through the use of technology and CT, which is defined as the study of hardware and software design related to algorithmic processes, such as their applications in society.

This form of learning aims to divide students into groups and come up with a big idea, which will be discussed by students and they will investigate the better solution, working in a collaborative way and developing communication, professional and technological skills. After that, they should develop and implement the best solution, which will be evaluated based on their performance and their results [62], [64].

The concept of a challenge is divided into Challenge, Mini-Challenge, and Nano-Challenge. The first includes the big idea proposed to students and they have to research it, familiarize, define main questions and think about a solution. The second is smaller than the Challenge and the students begin to put into practice the solution found through the concepts they know, thinking of a structure as a whole and then each specific task will be done in Nano-Challenges, which are focused on each specific skill and need the guidance of a teacher. Several Nano-Challenges can be incorporated to build one or more Mini-Challenges, which ultimately make up the Challenge [62], [64].

5.2 Summer Camp at IPB

Summer Camp is a course supported by the Polytechnic Institute of Bragança (IPB) every year, aiming to promote the Institution and to bring together students from technical and

secondary schools to develop activities based on science and technology. The 2019 Summer Camp edition was integrated into the RoboSTEAM project, with a methodology based on CBL, that uses robots and physical devices to develop Computational Thinking and knowledge in STEAM areas [62] [63].

This course took place at IPB for 5 days and involved 16 students divided into 4 groups. During all days, they were guided by 4 monitors and 2 teachers, as presented in figure 5.1. Whereas developing a challenge takes a long time, the course focused on developing a Mini-Challenge, which was subdivided into several Nano-Challenges for each of the groups [63].

Figure 5.1: Teachers, monitors and students who attended the Summer Camp [63].

Within the scope of physical devices is the application of the stroboscope. The purpose of the Nano-Challenge focused in this instrument was to teach students how to program microcontrollers using the Arduino platform and associate it with building a very useful device in the industry. Then, activities based on programming, such as blinking a LED, presenting messages on an alphanumeric LCD display and using buttons, were proposed to the students [63].

These little activities were created based on the main functions of the stroboscope, so that with knowledge acquired during the course, including programming in microcontrollers and a brief research on stroboscope did at the end of the course, they could understand better how to build the instrument joining all the previously developed functions, which consisted of the last activity. Besides that, they could learn the basic about the device, its operation and how it is used in real-world problem solving [63].

The figure 5.2 presented the first bench prototype of the stroboscope, which was used to demonstrate to students how the device works. On the left of the image is the electronic circuit schematic and on the right of the image is the real prototype, which has been explained in detail previously. Only with the exception of the lamp, which in this period was being used a 12V LED lamp that was later replaced by the individual LEDs [63].

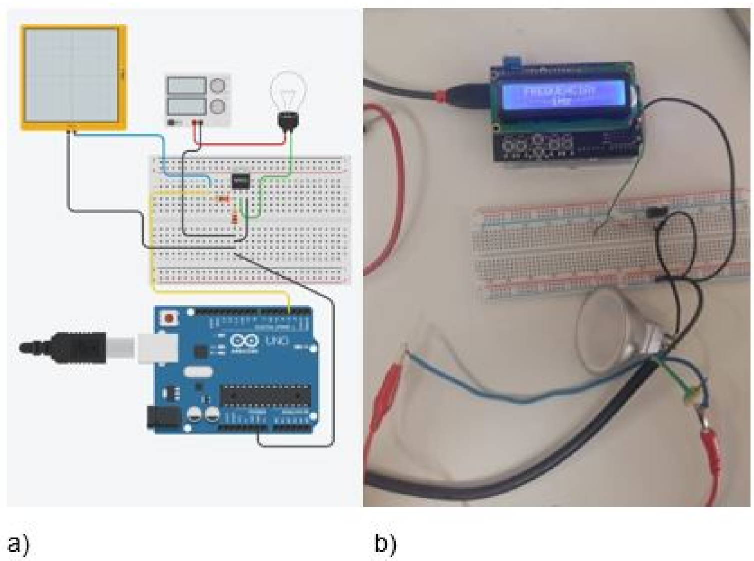


Figure 5.2: a) Electronic circuit schematic b) Stroboscope prototype [63]

In this Nano-Challenge were used some electronic components provided by IPB, such as protoboards, LEDs, resistors, buttons, jumpers, Arduino boards, among others. It was also used a fan with a mark just for demonstration of the stroboscopic effect through the use of the device [63].

The group for this Nano-Challenge was composed of three boys, average age of sixteen and all from secondary schools. Two of them already had programming knowledge but they haven't programmed in Arduino. The third student haven't had any experience with programming and microcontrollers previously. Therefore, before to start the tasks, it was taught the main concepts about microcontrollers, Arduino and how to program in an IDE [63].

The criteria of assessment were based, firstly, on the students' knowledge about Arduino, microcontrollers and STEAM concepts for the creation of activities according to

their level. During the Nano-Challenge, it was evaluated the time the students spent to finish the tasks based on the proposed time and the success in reaching the goal. To assist in the assessment the students also wrote a little paragraph, at the end of each day, describing what they learned in class. This way, it was possible analyze if they absorbed the information [63].

The group was composed of three students, two of them performed better, they used to finish the tasks first in relation to the other because they already know how to programming in C language, which is used in Arduino. About the summaries wrote by them, it was observed that they could understand the knowledge as desired [63].

It can be concluded that the students finished all the activities successfully during a time of approximately 3 hours per day. However, for the final challenge based on the stroboscope device, it would be necessary more time to execute it, being this more complex than the others. Even so, the students were doing correctly but they just didn't have enough time to finish it [63].

Chapter 6

Results and Discussions

This chapter presents the validation tests, that is, the tests to verify if the goals established were achieved and if the stroboscope prototype was able to measure the velocity of a rotating machine by visualizing the stroboscopic effect.

The rotation velocity of a three-phase motor, controlled in closed-loop and with a constant velocity, available in the laboratory, was measured using the stroboscope prototype and a commercial tachometer also available in the laboratory. The measured results of both devices were compared in order to realize the validation of the stroboscope. The motor was subjected to different voltages, then according to the voltage increases, the velocity also increases until it becomes stable. The table 6.1 presents the voltage values and the related velocities measured by the stroboscope and by the tachometer, which were very close.

The results comparison between the stroboscope and the tachometer can be better analyzed in figure 6.1, which shows the graphic of the devices' performance. Through this graphic it is possible to notice that the results of both instruments remained aligned and close, with an error practically insignificant. The graphic behavior shows the velocity increase according to the voltage increase and its stabilization around 1500 RPM.

The absolute error between the measurements was calculated and is presented in figure 6.2, which shows a graphic of the absolute errors for each voltage applied to the motor. The most error was in 225V, with an absolute error of 4,5V, but note that it begins to

Table 6.1: Measurements results table

Voltage (Volt)	Stroboscope velocity (RPM)	Tachometer velocity (RPM)
50	1455.66	1454
75	1482	1481
100	1491.75	1489
125	1494.5	1493
150	1497	1495
175	1497.5	1496
200	1500	1497
225	1501.5	1497
250	1502	1498
275	1502	1499
300	1501	1499

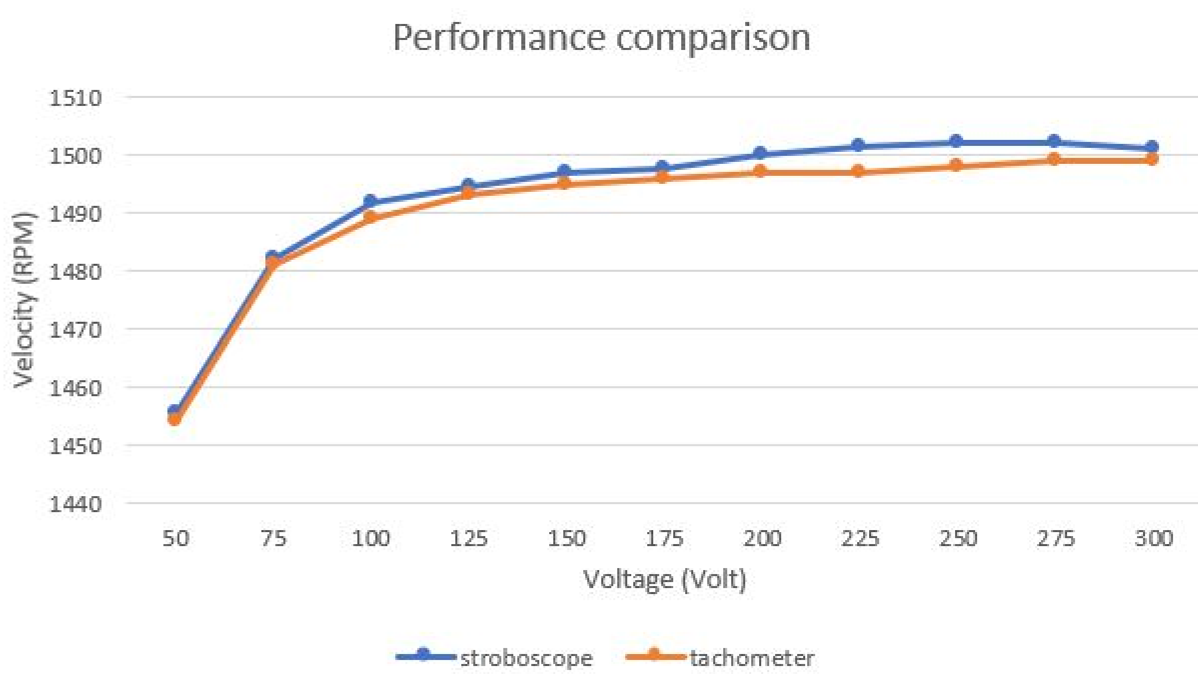


Figure 6.1: Graphic of the performance comparison between stroboscope and tachometer.

decrease again until 300V. It is important to take into consideration that the velocities measured by the tachometer are not exact because this equipment is not totally accurate and has measurement errors.

The velocities measured by the stroboscope were obtained visually through the stroboscopic effect, that is, at the moment that the machine appears stopped. A white mark

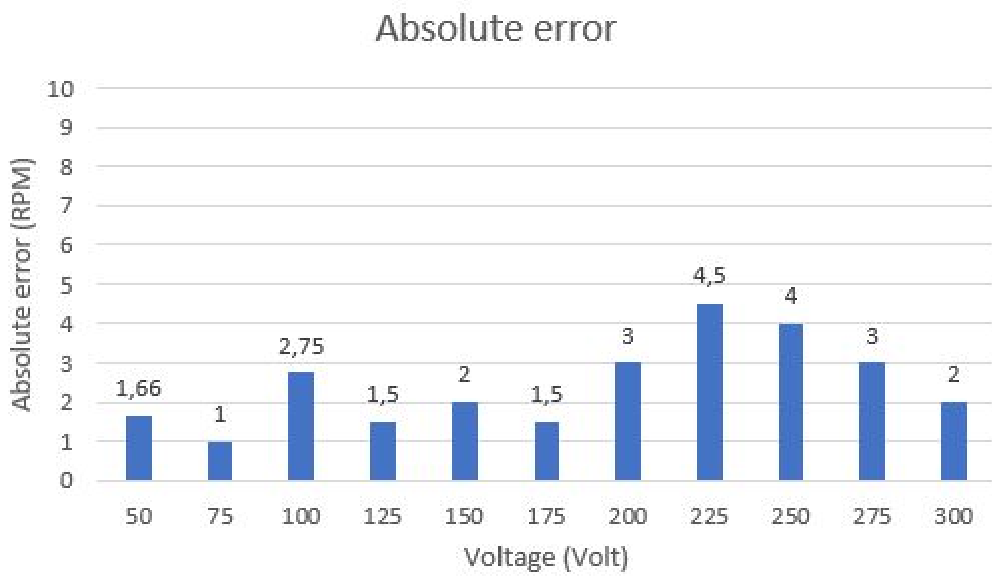


Figure 6.2: Graphic of the absolute error between the measured velocity values.

was done in the three-phase motor for the visualization of the phenomenon, which could be visualized successfully and without drag or blur.

There are presented below some images captured of the moment that the motor seemed to be stopped. It wasn't possible to realize measurements for velocities above 1500 RPM, because there isn't any equipment, available in the laboratory, that runs in velocities above that. The figure 6.3 a) was captured when the motor was running at a voltage of 175V and represents the moment when the flashes velocity is equal to the rotation velocity, so one mark is seen stopped and the velocity shown on the display, 1497.5 RPM, represents the machine rotation velocity.

The stroboscopic effect can be also seen when the flashes velocity is multiple or sub-multiple of the rotation velocity. In figure 6.3 b) the flashes velocity, 2995 RPM, is twice the rotation velocity. In each rotation, the machine is illuminated by two flashes and, as this process is too fast, the human eyes can't see this difference, so two marks are seen stopped because of the second harmonic. The same situation occurs in figure 6.3 c), but in this case, it is the fourth harmonic, that is, the flashes velocity, 5990 RPM, is four times the rotation velocity, so 4 marks are seen stopped.

If the flashes velocity is half of the rotation velocity, just one mark is seen stopped too and for this reason, measurement errors can occur. Therefore, it is important to start the measurement process with the stroboscope at high velocities or the maximum velocity of the device and then, decrease until to see just one mark stopped to have the assurance to find the right rotation velocity.

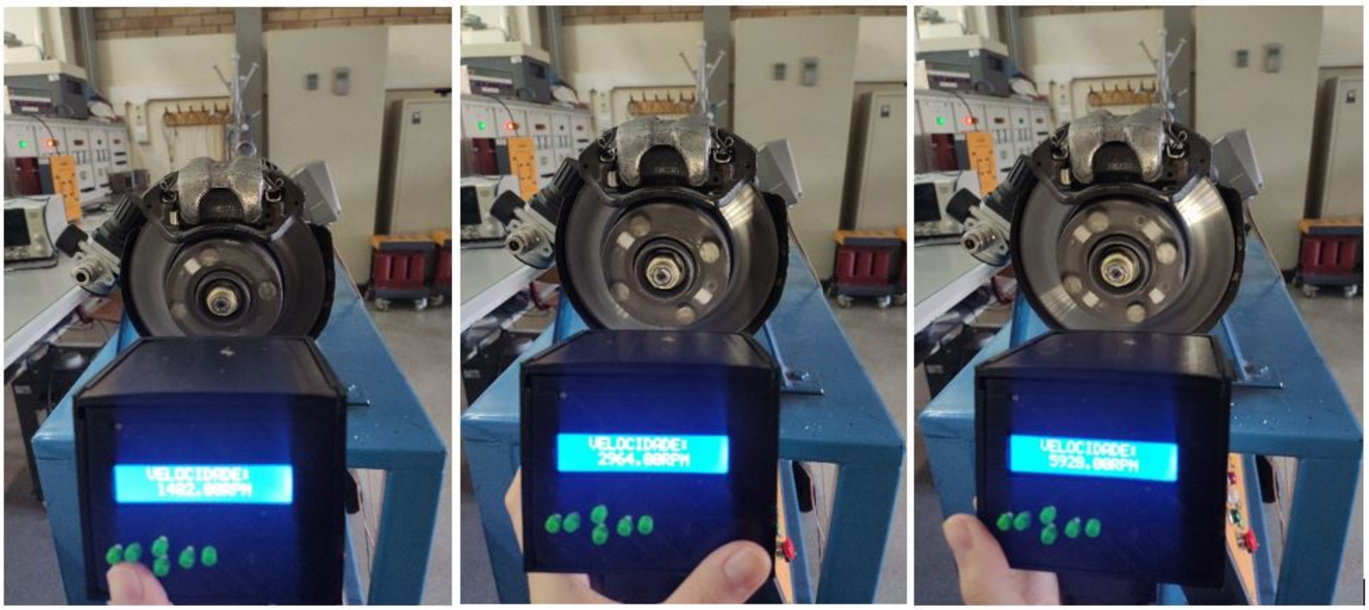
For example, imagine that the machine rotates exactly in 1000 RPM, it means that it does 1000 rotations per minute or about 16.67 rotations per second. If the stroboscope is pointed with the light blinking with half that velocity, it means that the light blink 500 times per minute or about 8.33 times per second. Then, during the interval time between one blink and another, the mark already did two rotations, so the flash can capture the mark at the same point, but in fact, the mark already passed twice. The stroboscopic effect will be seen and the machine will appear stopped, but that velocity is not correct.

a) b) c)

Figure 6.3: Stroboscopic effect images at 1497.50 RPM a) fundamental frequency b) second harmonic c) fourth harmonic

In figure 6.4 a) the motor was running at a voltage of 75V and a velocity of 1482 RPM, according to the stroboscope. The figure 6.4 b) represents the visualization of the

second harmonic and the figure 6.4 c) of the fourth harmonic. Therefore, the velocity value shown on the display in figure 6.4 a), where it is possible to see only one mark, is the rotation velocity of the three-phase motor.



a) b) c)

Figure 6.4: Stroboscopic effect images at 1482 RPM a) fundamental frequency b) second harmonic c) fourth harmonic

Chapter 7

Conclusion

In this work, a stroboscope prototype was developed, which was able to generate light blinkings at different frequencies, allowing to measure the velocity of rotate machines, through the stroboscopic effect visualization by the user. Such an effect could be seen successfully and without drag, proving that the period used for the duty cycle of the modulated signal was good.

The stroboscope behavior towards the user's action was shown plausible, confirming that the use of the function *delayMicroseconds* didn't influence the program performance. The tools and techniques used to manufacture the prototype were enough, whereas the stroboscope worked successfully and as expected.

Through the calibration process with an LDR sensor, it was possible to verify if the LED's response signal were consistent with the modulated signal sent to them and both presented the same period. Even though with the increased frequency the LDR sensor did not work well due to its limitations, the modulated signal sent to the LEDs at these high frequencies was consistent with what was designed. An alternative would be to use a faster light sensor.

The stroboscope validation was made comparing its performance with another measurement instrument. The velocities measured by the prototype proved to be very close to the velocities obtained by the commercial tachometer and although it does not have total accuracy of the measured values, both the results were similar.

The initial prototype could be applied in the scope of CBL in a summer course at IPB, which was part of the RoboSTEAM project, allowing that the students from secondary schools could learn to program microcontrollers based on a physical device, in addition to learn its importance in the industry and developing CT and skills in STEAM areas.

7.1 Future work

For a possible continuation of this work, some ideas are suggested below, in topics, like a way to improve the stroboscope.

- Developing a communication interface, allowing to send the velocity value read on the display to a computer for registration or processing.
- The application of the device in robots, for example, in a robot that can go to a place of difficult human access, like inaccessible machine parts.
- Creating a stroboscope more compact, in relation to physical size, which can be made using just the microcontroller and not all the Arduino board, and consequently, becoming it even cheaper.
- An improvement in the stroboscope implementing a battery level verification, through the use of a voltage or current sensor.
- Applying the stroboscope final prototype in another activities based on CBL.

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Appendix A

Firmware flowchart

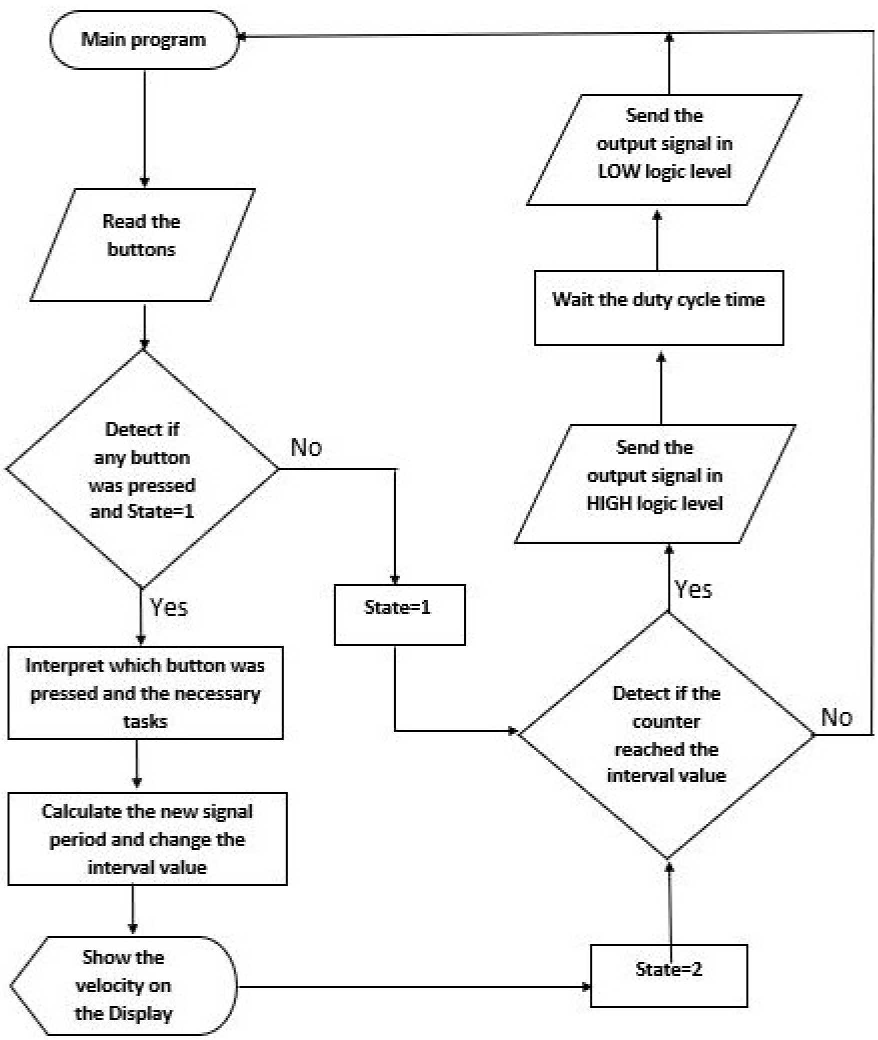


Figure A.1: Firmware flowchart.

Appendix B

Modulated digital signal images

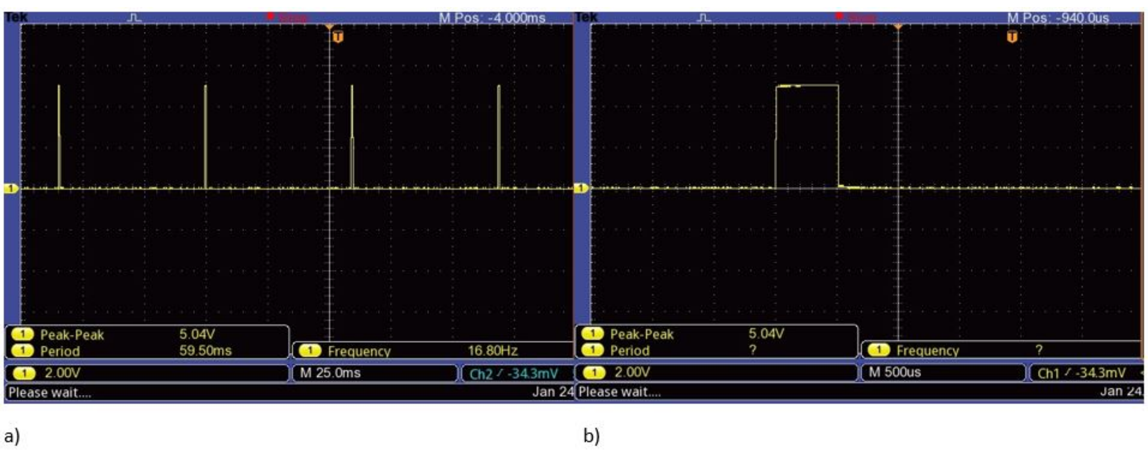
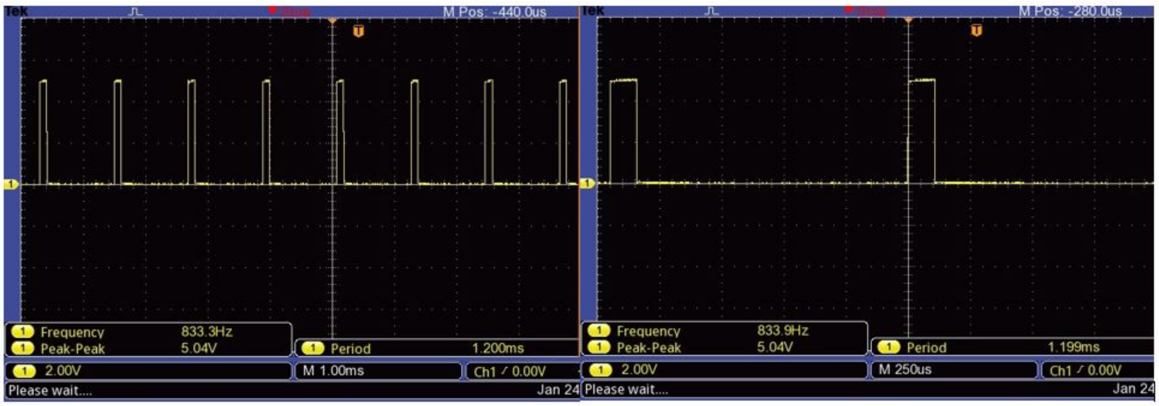
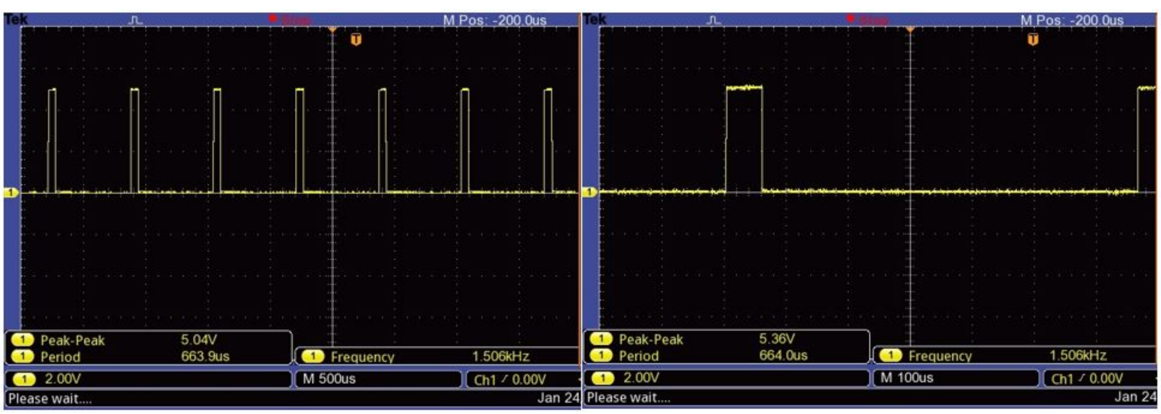


Figure B.1: Modulated digital signal at 1000 RPM



a) b)

Figure B.2: Modulated digital signal at 50000 RPM



a) b)

Figure B.3: Modulated digital signal at 100000 RPM

Appendix C

Calibration images

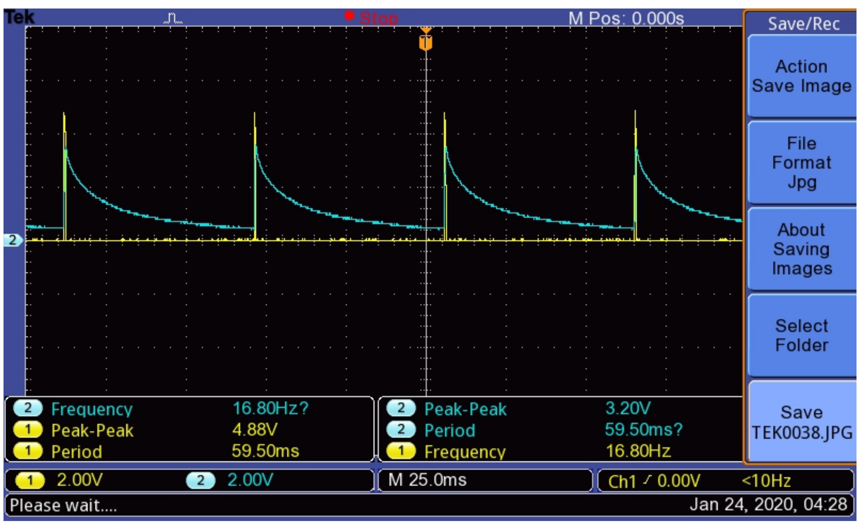


Figure C.1: 1000 RPM

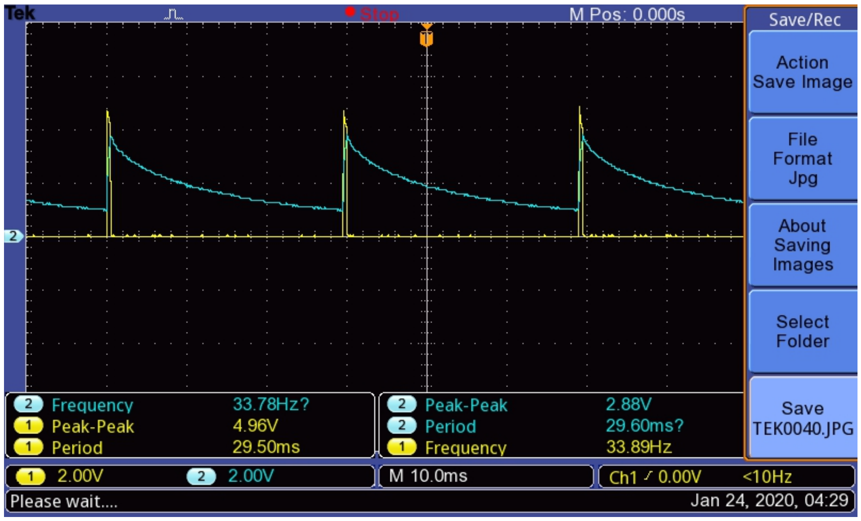


Figure C.2: 2000 RPM

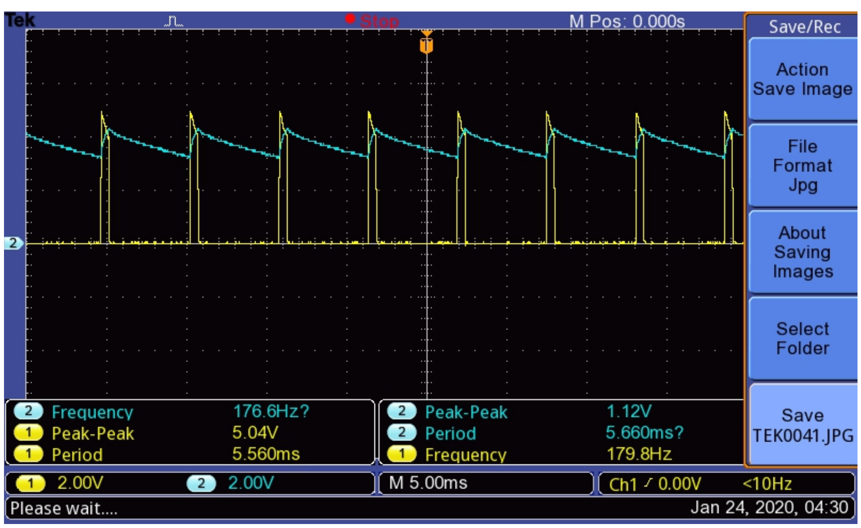


Figure C.3: 10000 RPM