Spectra Analysis of Different Light Sources Using a Homemade Spectrometer

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November 5, 2018

School Year 2018 - 2019

Abstract

Each light source has its specific properties. It is possible to determine its spectrum, its polarity, its cohesion... This paper will focus on light spectrum. However, the instruments used to measure this property, called spectrometers, can be very expensive or inaccessible to schools or non-professional users. The purpose of this paper is therefore to find an alternative to those expensive instruments.

To do so, economical and easy to find materials will be used: wood, a simple light sensor, a lens, a stepper motor and an Arduino board. It is important to take into account that the resolution and accuracy will be much lower than if we used a professional one, but it can be useful for educational purposes or some amateur projects.

In this paper, some theory is covered to understand how a spectrometer works and, then, it is described how the spectrometer was built, along with the materials used to do so. It is also explained how the electric circuit was built and how the code that controls it all works.

Six different light sources have been measured with the spectrometer and the results have been compared to the measurements obtained by a professional spectrometer. It has shown that it offers a cheap option, around 60 €, for schools and amateur projects.

Some possible future work, improving the spectrometer or building a better one, is also described in this paper.

CONTENTS

1 THEORETICAL BACKGROUND

1.1 Light as a Wave

Many theories try to explain what light is. The most widely accepted theory is wave-particle duality[1], which stays that light has both wave behavior and particle behavior. As a wave, it is considered an electromagnetic wave composed of a magnetic field and an electric field which have sinusoidal oscillation and that are perpendicular to each other[2]. As they are waves, they can be classified according to their wavelength or their frequency.

Wavelength (λ) is defined as the distance between peaks, or between troughs, of a wave. The whole electromagnetic spectrum contains a huge range of waves with different wavelengths, from a few pm to some km[3]. Visible light wavelengths measure hundreds of nm.

Frequency (v) is defined as the number of oscillations that a wave completes per second. It is measured in Hertz (Hz), and one Hz is equal to one oscillation per second.

As

$$v = \frac{s}{t} \tag{1}$$

, in which v is velocity, s space and t time; and wavelength has units of space and frequency has units of velocity^{-1}, these two units are related by the following expression:

$$c = \lambda v \tag{2}$$

Where c is speed of light measured in m/s, v is frequency measured in Hz (=s^{-1}), and λ is wavelength measured in m.

Color of visible light is determined by the wavelength of its waves. Visible light waves have wavelengths from approximately 380 nm (purple, with longer wavelengths than UV light) to 750 nm (red, with shorter wavelengths than infrared light)[3]. Visible light's spectrum is shown in Figure 1.

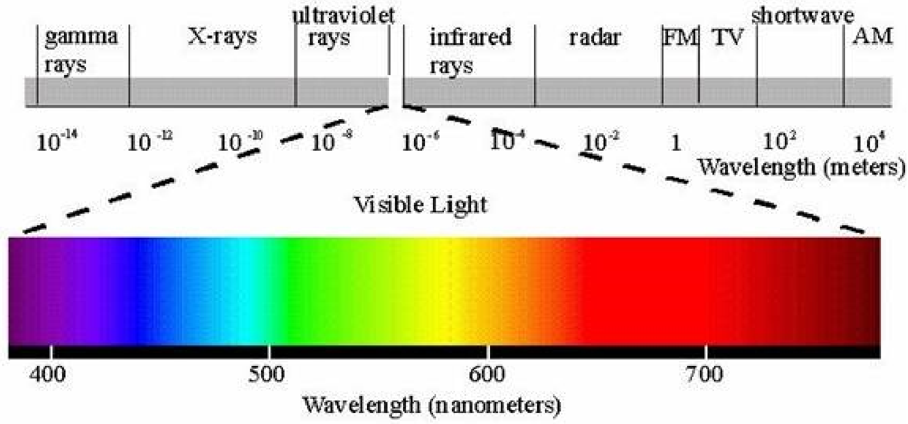

Figure 1: Classification of the whole electromagnetic spectrum according to its wavelength and, more in detail, the visible light spectrum with its colors according to their respective wavelengths.

Most light sources emit light beams that are composed of waves with different wavelengths. To analyze the frequency of the waves of a light source, a spectrometer is used.

This paper will focus on visible light, because our spectrometer will measure this type of light. The reason of doing this, is that visible light is the light we can see, it is easier to measure and its spectrometry is probably the most useful one in most cases.

1.2 Diffraction Gratings

The most important component in a spectrometer is the diffraction grating. When light formed by waves of different wavelengths goes through a transmission diffraction grating, beams of different wavelengths are *bent* more or less depending on its wavelength. The result of this is that all wavelengths are separated - in an ordered way - forming a kind of rainbow. This way, the light sensor of the spectrometer can measure waves of a specific wavelength.

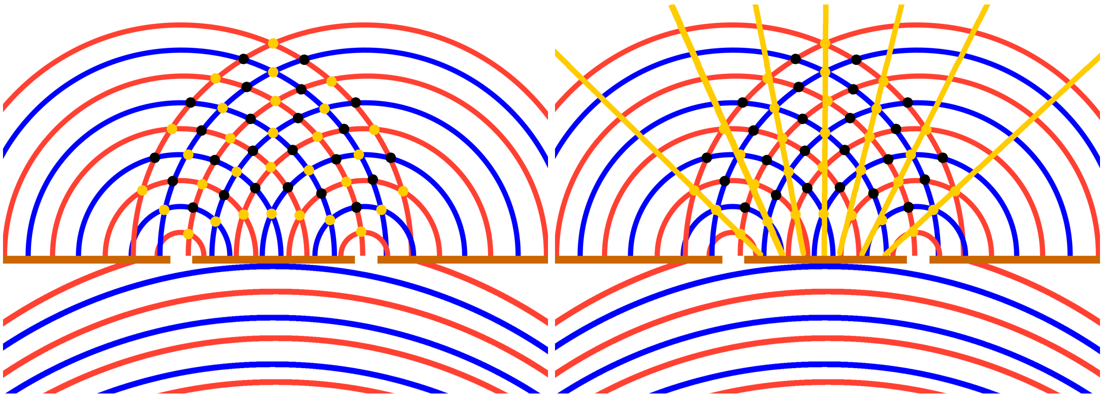

Figure 2: Interference of a wave going through a double slit (brown lines). Curved lines represent waves in which the red ones are the peaks and the blue ones are the troughs (or vice versa, as the result would be the same). Yellow dots show the points in which the waves are totally constructive and black dots, where they cancel each other out. Yellow lines show light in the end, forming an interference pattern.

Transmission diffraction gratings have a huge amount of very tiny slits very close to each other. When a light wave goes through these slits, as it is a wave, a new wave is formed in each slit (Figure 2). When these newly formed waves meet, an interference is produced: peaks with peaks form bigger amplitude peaks, troughs with troughs form bigger amplitude troughs and peaks with troughs cancel each other out. Where waves cancel each other out, there is no light. The result of this is an interference pattern, there is an alternation of light and darkness. If this happens with two slits, the result is something similar to the diagram of Figure 2.

If instead of two slits, we have a huge amount of very tiny slits very close together - as in the diffraction grating -, we observe a different thing: instead of lighter and darker patterns, we will observe only a few light points and total darkness everywhere else. These points are located where all waves of the slits perfectly add to each other. As there are so many slits, all the other points disappear as waves destruct each other, because there are a lot of waves and there is always someone which each wave can be canceled out with.

To understand this behavior, Figure 3 may be very useful:

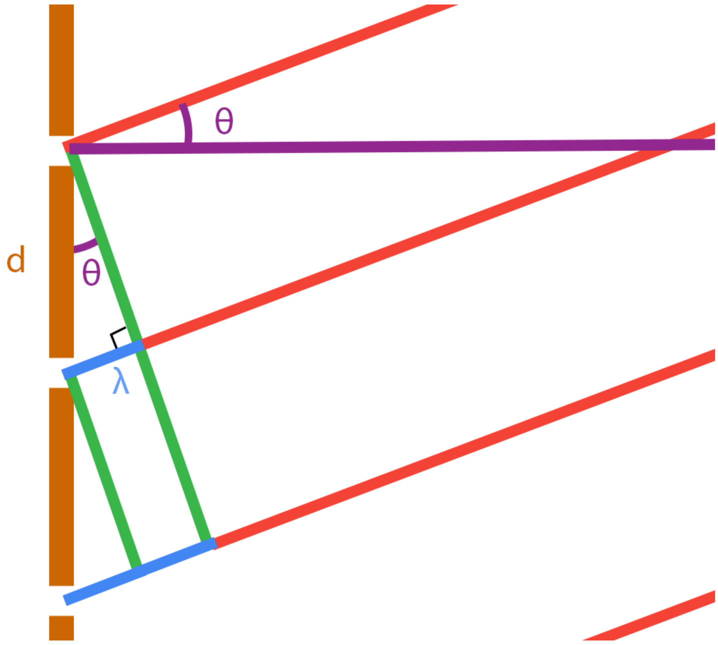

Figure 3: Diagram of a diffraction grating. The brown line is the diffraction grating with its slits, red lines show the directions to a light point, blue lines represent the offset of the waves following the red directions and purple lines show the angle θ.

Light points appear where all waves are in phase. This means that the offset between them is a multiple of their wavelength. As the size of the slits and the space between them is very small in comparison with the distance to the light point, the directions to the light point - in red in the figure - can be considered parallel. Therefore, the offset of the waves is what in the figure is blue colored. We can imagine a right triangle as shown in the figure. And as the offset must equal wavelength, we can relate the angle with wavelength as follows:

$$\lambda = d \, sin\theta \tag{3}$$

, where λ is wavelength, d is the distance between slits, and θ is the angle - that will be equal to the angle between the direction from the diffraction grating to the light point and the perpendicular direction to the surface of the diffraction grating.

d is usually measured in lines/mm, and it is indicated in each diffraction grating by the fabricant.

When light with multiple wavelengths goes through the diffraction grating, each wavelength is diffracted to its specific angle, and the spectrometer is able to measure them.

1.3 How Do Spectrometers Work

To know which wavelentghs are more present in a light form a particular light source, spectrometers measure the intensity of each wavelength. They use diffraction gratings to spread all wavelengths and a sensor measures light intensity at each wavelength.

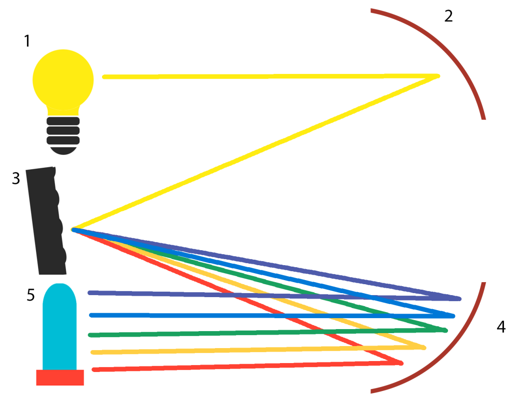

Figure 4: Spectrometer working diagram with (1) the measured light source, (2) collimating mirrors, (3) the diffraction grating, (4) focusing mirrors and (5) the sensor.

A spectrometer consists of a few components[4]. First, the light to be measured goes into the spectrometer and bounces on a collimating mirror, which makes all the beams go in the same direction – otherwise they could not be correctly diffracted. Secondly, light is diffracted by a diffraction grating slide. Light is reflected by it in different directions according to its wavelength, so they can be measured separately. Finally, another mirror is used to focus this diffracted light to the detector, which is normally an array of diodes – so many wavelengths can be measured at once – which measure the intensity of light at each wavelength. Either the grating, the mirror or the sensor can move so the sensor is able to read the different wavelengths.

With all the information explained in this section, a homemade spectrometer can be built. But some changes need to be implemented. First of all, as a collimating mirror can be very expensive, a lens (ideally a plano-convex one) has been used instead. Secondly, although the diagram above shows a reflective diffraction grating, a transmission one has been used instead, as they are much more inexpensive. Thirdly, we can prescind from using a focusing mirror or lens after the grating, so light will go directly to the sensor. Finally, instead of using an array of diodes, only one diode will be used, and it will move along the whole spectrum (of visible light).

2 EXPERIMENTAL PART

2.1 Materials

A 35 mm Ø planar-convex lens, a 1000 lines/mm diffraction grating slide, an Adafruit TSL2591 light sensor, a 200 steps/rev stepper motor and an Arduino Uno board were used to build the spectrometer.

As well, some wires, a 220 Ω resistor, two 10 kΩ resistors, two push buttons, a piezo, an L293D motor driver, some cardboard, a sheet of wood and some screws were also used. The whole materials list along with some specifications can be consulted in the Appendix.

2.2 Design

The homemade spectrometer has been built using the following diagram:

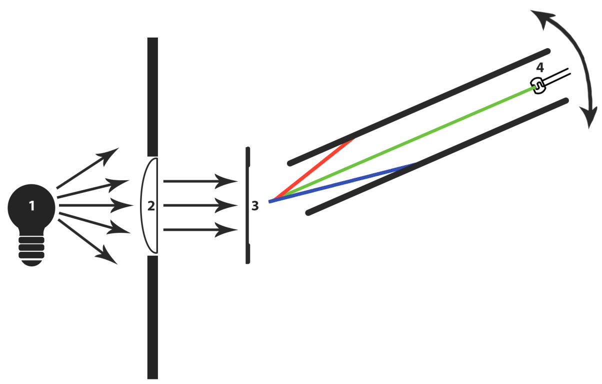

Figure 5: Homemade spectrometer working diagram. Model with (1) any light source we want to measure, (2) a lens in an opaque screen, (3) a diffraction grating and (4) a sensor placed in a rotating arm.

In this diagram, at the beginning light of the desired light source (1) goes in all directions. The collimator lens (2) is placed in an opaque screen which blocks light that does not go through the lens. The collimated light passes through the diffraction grating (3) which separates the light in all its wavelengths. Finally, the sensor (4) placed in a rotating arm – being the diffraction grating the rotation vertex – so it can be moved to measure just the desired wavelength.

Once the working diagram was clear, and before the construction of the spectrometer, a 3D model was made to calculate some dimensions and to ease the construction itself. It can be observed in Figure 6.

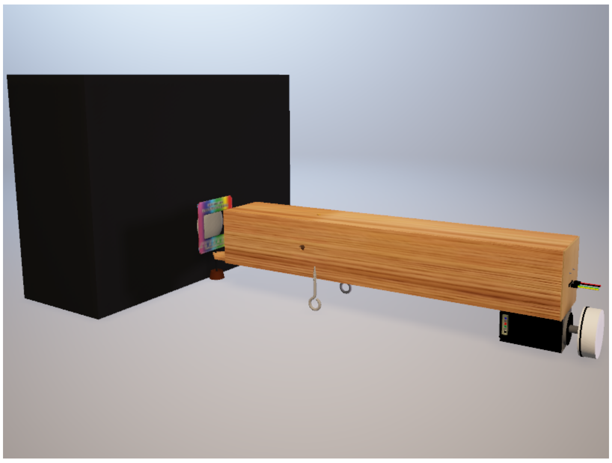

Figure 6: 3D model of the spectrometer. It has real dimensions and materials and takes into account many details that helped during the building process.

In this figure, the light source would be behind the shoe box, which will be the opaque screen mentioned above. The lens would be placed in a hole in the shoe box and the diffraction grating slide would be just in front of the lens. A wooden square prism would be used as the arm in which the sensor would be placed so it could move. It would be held using with a nail in a hole and supported by two screw eyes. To move the arm, a stepper motor with a plastic cap would be used as a wheel, placed at the end of it.

2.3 Building Process

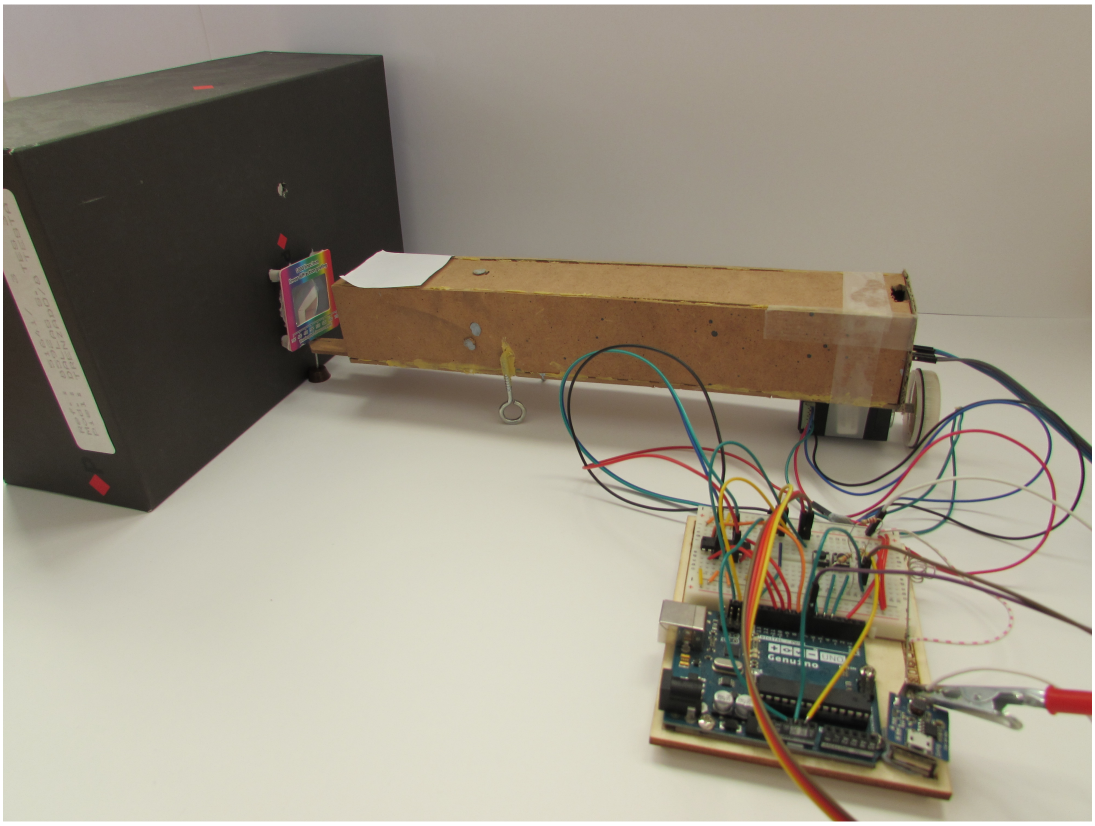

Figure 7: Final homemade spectrometer built as explained in the following sections.

2.3.1 Arm and wheel

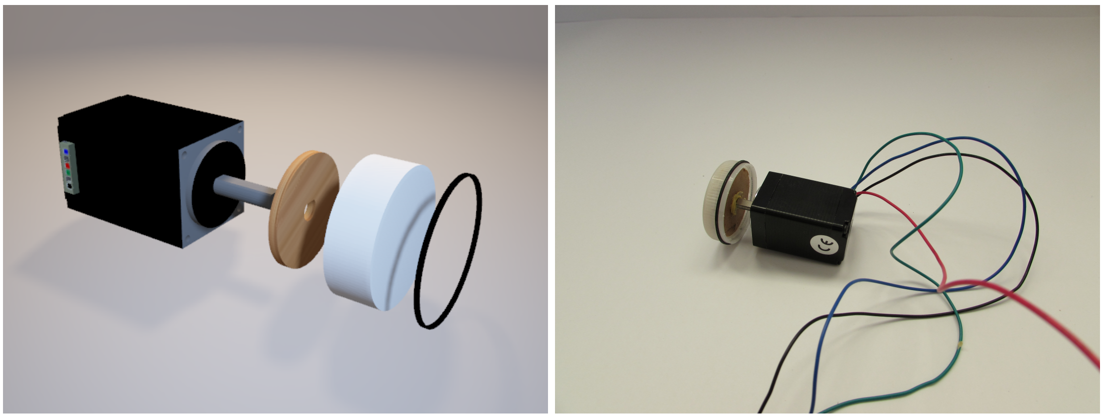

Figure 8: The wood wheel was glued to a plastic tap and a rubber band was added. Then, the stepper shaft was put in the wheel.

First of all, the wooden wheel of the stepper motor was made. A 3.5 cm diameter circle was cut from a 3 mm thickness wood sheet. A 5 mm diameter hole was made in the center of the wheel, in which the stepper shaft was inserted and glued. Then, the wheel was glued to the inner side of a 4 cm diameter and 1 cm thickness plastic cap. This was done so as to be able to place a rubber band around it. The rubber band would provide much more grip to the wheel.

Figure 9: Four wooden rectangles formed the square prism. Another piece of wood and a nail where used to fix the angle of rotation, held by a cylindric plastic piece.

Afterwards, four 30 x 5 cm rectangles were cut from a 3 mm thick wood sheet. They were glued together assembling a square base prism. The stepper motor was attached to one end of the prism with the wheel facing out. Adhesive tape was used with the intention of being able to remove the motor if needed afterwards. Two screw eyes were also glued to the middle of two sides of the prism to be used as supporting points. As they are made of metal and are rounded, friction is decreased.

As the movement of the wheel had to be circular and with the centre right under the diffraction grating, something to keep one end in place was needed. A 2.5 cm wide piece of wood was glued to the bottom side of the prism in a way in which it protruded 5 cm from the end of the prism. A nail was driven at the end of that piece. It would be the centre of the circular movement of the wheel. The nail would be placed in the 1.5 mm diameter hole of what originally was a shelf support. It is just a plastic cylinder of

1 cm diameter and 0.5 cm tall. As the cylinder would be glued just in front of the box, right under the diffraction grating, the corners of the piece of wood where the nail was were cut so they would not hit the box preventing the sensor from moving.

2.3.2 Lens and diffraction grating

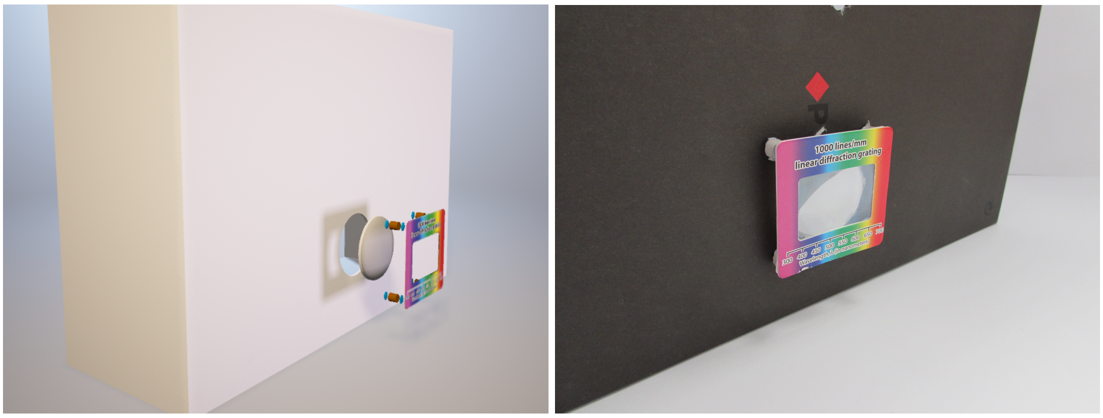

Figure 10: The lens was placed in a cardboard box side. The light source would be placed in the other side of the box and light would only pass through the lens. After passing through the lens, it would pass through the diffraction grating, held with Blu-Tack.

To hold the lens, a hole in a cardboard shoe box was made. The box was used to block the light that did not go through the lens. As the sensor would be approximately at a height of 5.5 cm, the center of the hole was also there. The lens fitted perfectly the hole, which was circular with 3.5 cm of diameter, so it did not have to be glued or fixed in any other way.

The light source would be placed in the inner part of the box, so the diffraction grating slide was placed outside, in front of the lens. The intention was to attach it directly to the box using Blu-Tack, so it could be adjusted or removed. But, as the lens protruded from the box, some small cylinders made of rolled thin cardboard, were placed in between; all was joint using Blu-Tack. Moreover, by doing this, the nail - center of the circular movement - could be placed right under the grating.

2.3.3 Sensor

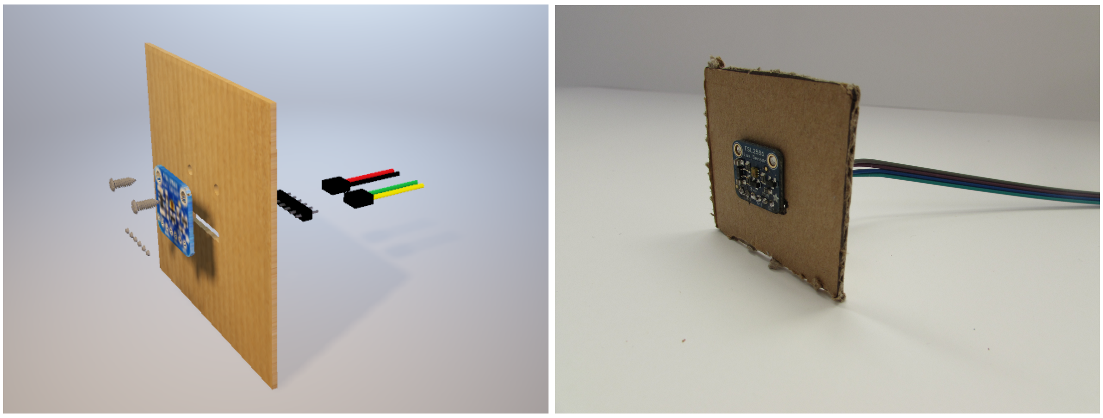

Figure 11: The sensor was placed on a cardboard sheet - at the end of the rotating arm -, soldered to some pins and connected to Arduino using jumper wires.

To measure light intensity, a TSL2591 light sensor was used. This sensor was used because it is inexpensive and pretty accurate.

To connect the sensor with Arduino, it was soldered to six male headers. A chain of male-female jumper wires were used to connect the male headers to the breadboard. Jumper wires were used because they are designed to work with breadboards, making all the process much easier. They were male-female because we needed to connect the male headers to the female wholes of the breadboard.

Although the sensor has six pins, only four of them were needed in this project, so two of them were left disconnected. This is better explained in Section 2.3.5.

A 5 cm x 5 cm piece of cardboard was cut to place the sensor at the end of the rotating arm. Some wholes were made to it: one rectangular, through which the wires would go; and two circular ones, to hold the sensor with two screws attached to the top wholes of it. Finally, this piece of wood was placed at the end of the rotating arm using adhesive tape, so it could be removed if needed.

2.3.4 Improving collimation

Collimation could not be perfectly achieved by the lens used. This could be a problem because if not all light went in the same direction, light of different wavelengths could meet at the same point and the measurement would not be exact.

After the first measurements, this was confirmed. To prevent wrong direction beams from reaching the sensor, two cardboard rectangles similar to the sides of the wooden arm were placed in it with a separation of 0.75 cm approximately. Reducing the width of the arm through which the beams could travel, many diagonal - uncollimated - paths were removed. These cardboard pieces were also painted mate black so they would absorb the beams which reached them instead of being reflected and possibly reaching the sensor. Moreover, two rectangular pieces of wood were put at the beginning of the arm separated by 0.25 cm so as to help to block uncollimated light.

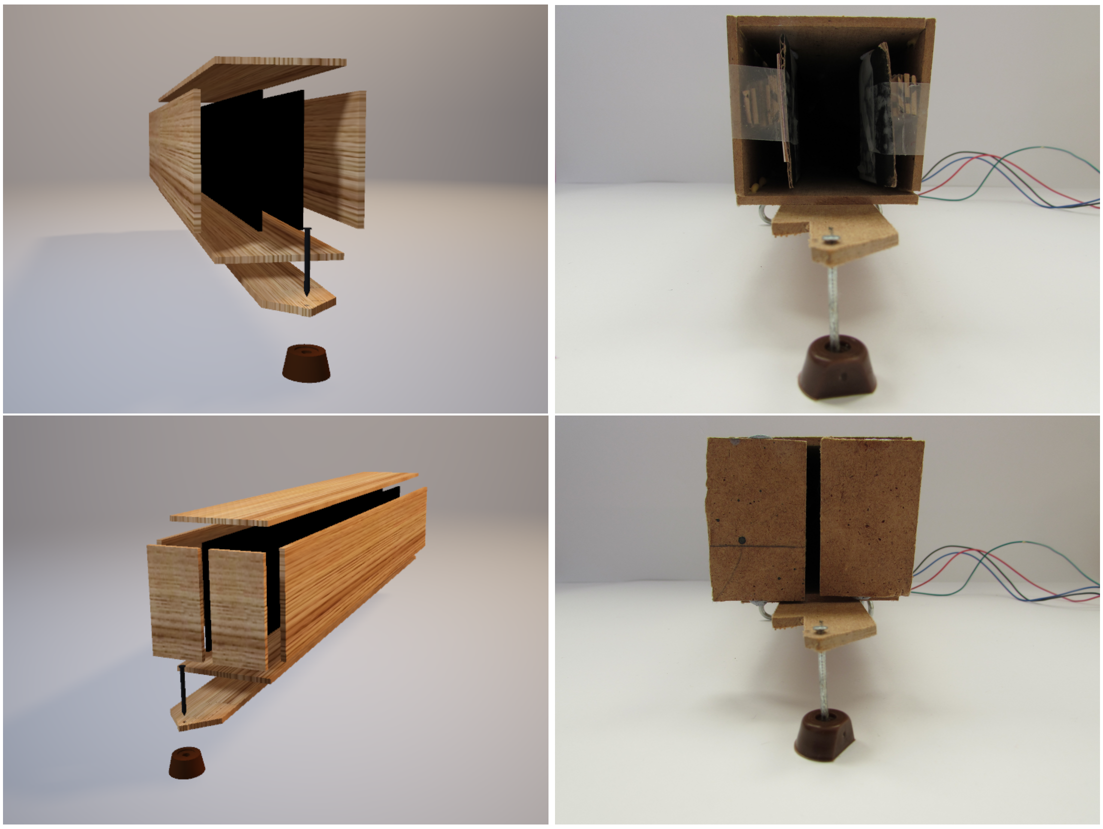

Figure 12: Two black-painted cardboard rectangles prevent uncollimated light from reaching the sensor.

This small change produced big improvements in the results, as can be seen in Section 3.

2.3.5 Circuit

An Arduino Uno board was used to build the circuit. Arduino would control the movement of the stepper motor and manage the received data of the sensor. It was also used to power some light sources afterwards. The whole circuit is shown in Figure 13:

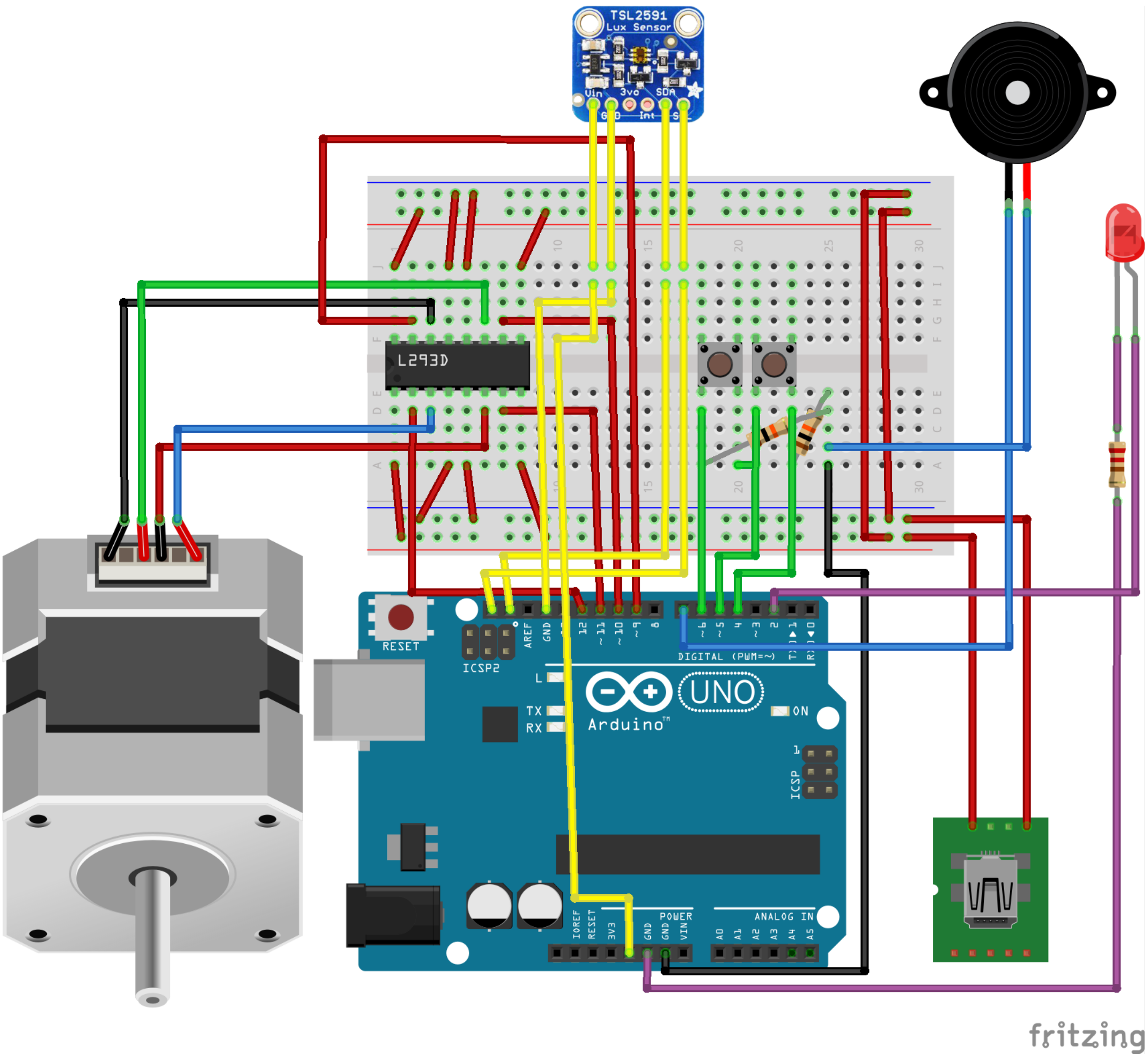

Figure 13: Fritzing diagram of the whole circuit. In yellow, the sensor circuit; in red (plus the motor wires' colors) the motor circuit; in green, a two-button circuit; in blue, the circuit of the piezo; and in purple the circuit used to power the LEDs.

Firstly, the circuit to control the stepper was made. As Arduino cannot directly control stepper motors, a driver (L293D) was used. Its internal circuit can be observed in Figure 14. Pins 4, 5, 12, 13 were connected to ground; pins 2, 7, 10, 15 were connected to output pins 12, 11, 10, 9 from Arduino; pins 3, 6 were connected to coil A from the stepper motor and 11, 14 to coil B; pins 1, 8, 9, 16 were connected to 5 V. An external source was used to supply power. This was done because the motor has a high power consumption and its movement can cause voltage drops, which can affect the sensor's measurements. The external source used was a micro USB taken out from a power bank connected to a 5V smartphone charger.

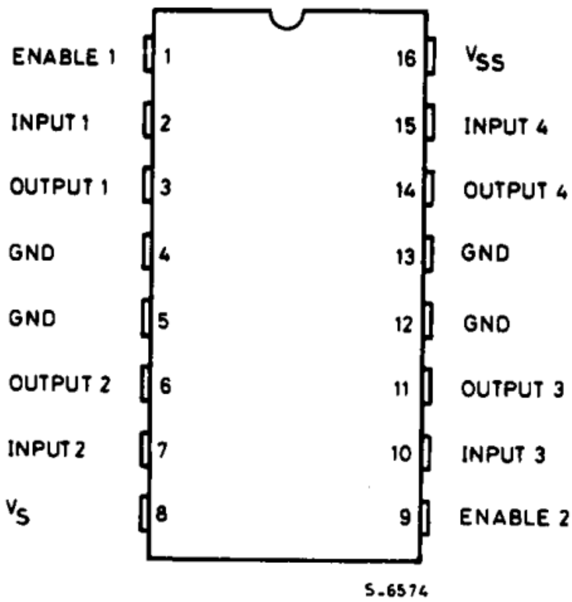

Figure 14: L293D pins scheme obtained from its datasheet[5].

Secondly, the TSL2591 sensor circuit was built. This sensor has an internal circuit and it can connect to Arduino using six pins - Vin, Gnd, 3vo, Int, SDA, SCL - but, as explained in Subsection 2.3.3, only four of them were connected to Arduino.

The communication with Arduino, receiving orders and sending data, is achieved through a protocol called I^2C. This protocol uses two wires - SDA and SCL - to send bytes of data using electric pulses. The SDA and SCL pins of both components were connected through a chain of jumper wires.

TSL2591 can be either powered using 3 V or 5 V. In this case, 5 V were used because Arduino One board does not have a 3 V output pin - just a 3.3 V one, which is too much. So the Vin - Voltage in - pin of the sensor was connected to the 5 V pin of Arduino through jumper wires and the 3 V pin of the sensor was left disconnected.

There is one pin of the sensor left, the Int one. It stands for Interrupt and it is used to interrupt some processes. As this feature is not needed for this project, this pin was not needed; so it was left disconnected too.

Some other components such as the buttons, the piezo and the LED were added to the circuit. These were not strictly necessary for the spectrometer to work, but were useful in some cases.

The two buttons were connected to power - in this case to the pin 7 - and to input pins so they could be used to control Arduino easily. As it is explained in Section 2.4, they were used to pause and resume the measurements.

A piezo is a component that vibrates and creates sounds. Using it enhanced the user experience and made it much easier to notice some things that were happening, as the measurements near to end. This is better explained in Section 2.4 too.

Finally, as in this project many LEDs were analyzed, they were powered with Arduino using two wires and a 220 Ω resistor.

2.4 Code

An Arduino code controls all the components of the circuit and then sends the data to a Python script that processes it, displays the graph and creates the result files.

Arduino has to be connected to the computer with the Python script through USB - to be powered and to be able to communicate with Python - and the micro USB source of the stepper needs also to be connected to a power source - if not, the arm would not move. Once connected, the Arduino code starts to run automatically, causing the piezo to make a sound and, if connected, the LED to shine. However, measurements do not begin until the Python script is executed and the correct button is pressed. It is also very important before pressing the start button to be sure that the rotating arm is placed perpendicularly to the lens.

To start the measurements, the Python file has to be executed. When it starts, it asks which light source is being measured - this information will be used to title all the graphs and files. After that, using a module called *pySerial*, the Arduino board is reseted and the Arduino code is run from the beginning. A piezo sound indicates that the Arduino code has started again.

Immediately, the Python script asks the start button to be pressed. Two push buttons have been placed in the circuit. The button with the output connected to the pin 6 of Arduino starts the program, or resumes it in case it is paused. The button connected to pin 4 pauses the program, stopping the movement of the rotating arm and the measurements of the sensor.

When the start button is pressed, the piezo plays a tone and the arm - controlled with the *Stepper* library of Arduino - moves to the starting position. Visible light has been defined above as light between 380 nm and 750 nm but, to have some more margin, the starting position has been set at 350 nm. To know how many steps are needed, some calculus has been done.

First of all, the starting position's angle can be found using the diffraction equation explained in Section 1.2:

$$350 = 1000 sin\theta$$

$$\theta = sin^{-1}(\frac{350}{1000}) = 20.49°$$

Knowing the angle, it is easy to know how much distance the stepper has to move. We just need to know the radius of the circular movement, which is the arm length (34 cm).

$$20.49° \, \frac{2\pi 34 \; cm}{360°} = 12.16 \; cm$$

The shaft of the stepper turns 1/200 rev each step and the wheel radius equals 2 cm, so:

$$12.16 \; cm \, \frac{1 \; rev}{2\pi 2 \; cm} \, \frac{200 \; steps}{1 \; rev} = 193.49 \; steps$$

Although the exact value equals 193.49 steps - that would be approximated to 193 steps - it has to be taken into account that the radius lengths are not exact and that the wheel does not have a perfect grip. So a test was done approximating that to 200 steps and the angle it moved measured 20.5°, which is almost the angle of 350 nm - it exactly equals 350.2 nm.

Once the arm has reached the starting position, it starts to move slower. The stepper makes a step, the sensor measures intensity and, with the number of steps done - counted by Arduino - , Arduino calculates and sends the wavelength measured and its light intensity to the Python script. After each step, there is a delay of a second to ensure there are no timing problems. This process is repeated until the end of the measurements.

To control the sensor and read and process its values, the *Adafruit Sensor* library for Arduino along with the specific *Adafruit TSL2591* library are used. The *Wire* library is also required to use the I^2C protocol.

To know which wavelength is being measured, the code could perform an easy calculus with the radius of the wheel, the radius of the arm and the number of steps done, but, as said before, the radius lengths and grip are not perfectly known. In this case would be even more inexact, because it stops after each step, creating some big accelerations that make the grip decrease. Instead, a test was done and after 329 steps - counting the first 200 - it moved 32.5 ° from the perpendicular with the lens. So each step moved:

$$1\ step\ \frac{32.5 - 20.25°}{329 - 200\ steps} = \frac{12.5}{129}^{\circ} = \frac{25}{258}^{\circ} = 0.097°$$

Knowing this value, after each step, Arduino calculates the wavelength being measured using the following function (being x the number of steps):

$$\lambda = 1000 sin((x - 200)\frac{25}{258} + 20.5)$$

So much precision with the numbers, using fractions, would not be really needed, as the angle measurement was a little inexact and not all the steps are equal, but it was easier and safer not to round those values.

To send this data to the Python script, the Arduino code just prints it in the *Serial Monitor*, using the *Serial* library. Then, the Python script, using the module *pySerial* mentioned above, reads the *Serial* and gets the data. Both wavelength and intensity are printed on the Python Shell so it is possible to know the exact values. Using the library matplotlib, Python is capable to display the information in a live graph that updates after each step, so it is possible to watch how the spectrum progressively forms from the lower wavelengths to the higher ones.

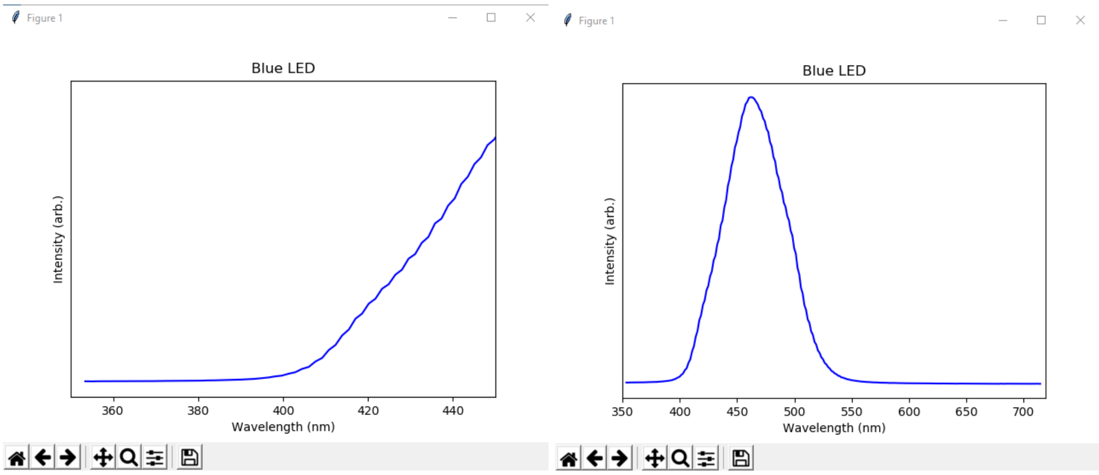

Figure 15: Same Python live graph at two different points: near the beginning ($\lambda \approx 450$ nm) and near the end ($\lambda \approx 725$ nm).

Although the light analyzed in this paper is visible light and has been defined before as the light between 380 nm and 750 nm, not all spectra were measured exactly between this points. All measurements started at 350 nm to have some margin and, as each light source is different and the results are obtained as soon as they are measured, the choice of when to end the measurements has been given to the user. This way, if, for example, the user discovers something interesting near the 750 nm, he can take the decision to end the measurements later on. To do this, the arm movement and the sensor readings loop forever; the Arduino program does never end. When the live graph window is closed, the Python script automatically stores the graph as an *svg* image and all data - wavelengths and intensities - in a *cvs* file. A *cvs* file is used because it can be edited with any simple text editor, it is supported by almost any data managing program - such as Excel - and does not require any hard encoding - data is simply separated by semicolons. It is important to notice that, although the Python script stores the data and then stops running, the Arduino code keeps running, as said before. This means that the arm continues moving. To stop this, the pause button is very useful, so it is recommended to first press the pause button - two short sounds will be emitted - and then close the graph window, as pausing the program does not affect data in any way and the program could be resumed whenever wanted just pressing the start/resume button - one long sound would be emitted. Moreover, to help the user, the piezo emits a sound after each reading above the 700 nm, so the user notices it is getting near the 750 nm.

A Python script to plot different spectra stored in *cvs* files in a single graph has also been developed, although this could have also been done with many other programs such as Microsoft Excel. The advantage of using this script is that it automatically maps the intensity, as it is an arbitrary unit and, to compare spectra, it does not matter which light source is brighter.

3 RESULTS

The spectrometer was able to successfully measure the spectra of six different light sources - red, green, blue and white LEDs, an incandescent bulb and a green laser. To rate its quality, the same light sources were measured with a professional spectrometer (*Princeton Instruments Acton Series 2500i*, with a focal length of 500 mm, a resolution of 0.05 nm at 435.8 nm and an accuracy of ± 0.05 nm[6].) from ICFO - Institute of Photonic Sciences. Resulting spectrometries from both spectrometers have been compared and discussed below.

Also, analyzing the resulting spectrometries and doing some calculus, some technical specifications of the spectrometer have been found, they can be seen below too.

3.1 Spectrometries

3.1.1 Color LEDs

All LEDs analyzed with the spectrometer were LEDs from the *Arduino Starter Kit*. To perform the measurements, they were powered with 5 volts through a 220 Ω resistor using Arduino. The results can be observed in the spectrometries of Figure 16.

The spectrum obtained of the blue LED - with its peak at 460 nm according to its datasheet[7] - was some nm below the reference one. The reference spectrum had its peak at 451.014 nm while this spectrometer's spectrum had it at 456.9 nm, so there was a difference of 5.9 nm.

The spectrum of the green LED - with its peak at 570 nm according to its datasheet[8] - was the most accurate measurement according to the reference spectrum. It was found that its spectrum has, in fact, two peaks; which can be observed in both spectrometries. The reference spectrum presents them at 555.416 nm and 561.804 nm while this spectrometer's spectrum presents it at 553.1 nm and 558.7 nm respectively. That is just 3 nm of difference each (exactly 2.3 nm and 3.1 nm).

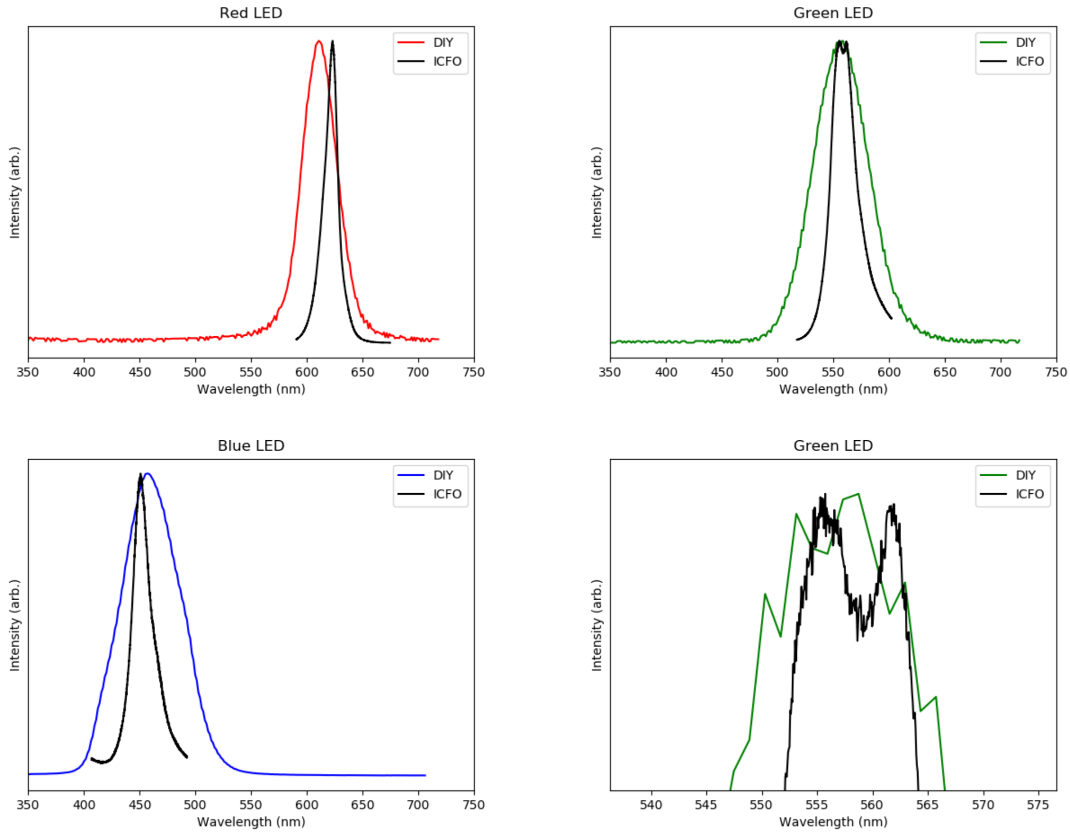

Figure 16: Colored plots represent the spectra obtained with this paper's spectrometer and black ones are the spectra obtained with the ICFO spectrometer, that are used as reference.

The red LED - with its peak at 630 nm according to its datasheet[9] - presented the most displaced spectrum of all the color LEDs measured with the spectrometer. The peak of the reference spectrum is located at 623.228 nm, while this paper's spectrometer spectrum locates it at 610.9 nm, that is a difference of more than 10 nm (12.3 nm), the double of the difference between the blue LED spectra.

It has to be considered that these datasheets' *Peak Wave Length* - as is mentioned there - are approximated. For this reason, the professional spectrometer measurements have been taken as reference.

Although the spectra are displaced, they have the same shape as the reference ones, a bit deformed by the width increase - explained below. This can be observed in the bottom right graph, in which the two peaks of the spectrum can be seen in both plots. This fact confirms the quality of the sensor.

The displacement of the peaks must be caused by wavelength calculus of the code. The errors in this calculus could be caused either by irregularity in the movement of the stepper motor or the wrong measurements of the stepper movement used to calculate it. The movement of the stepper motor consists on moving and stopping a lot of times, so a lot of acceleration is present, which may cause grip variations and, in consequence, an irregular movement that could move more in some parts than in others. The measurement of the movement was done using a regular protractor, so there could be inexactitudes that could affect the function used to calculate the wavelength. The displacement to the central wavelengths suggests that, in case they are caused by the wrong measurement of the movement, the starting position is probably considered higher than how it really is and the movement per step is considered lower than it really is. Possible solutions to these problems are presented in Section 4.1.

The cause of the homemade spectrometries being much wider than the professional ones is probably the not perfect collimation. As the lens of the spectrometer is not very good, collimation is not done perfectly and, even reducing the wrong paths with the *collimation improvements* of Section 2.3.4, some uncollimated light reached the sensor. Uncollimated light that reaches the sensor, cannot be very far from where it was supposed to be, because it would be blocked by those collimation aids mentioned above. For this reason, it does not affect a lot to the shape of the spectrometry, but it does make wider the zone of light detection, as the sensor detects a little light that should not be there that is coming from near wavelengths. These can be observed in Figure 17.

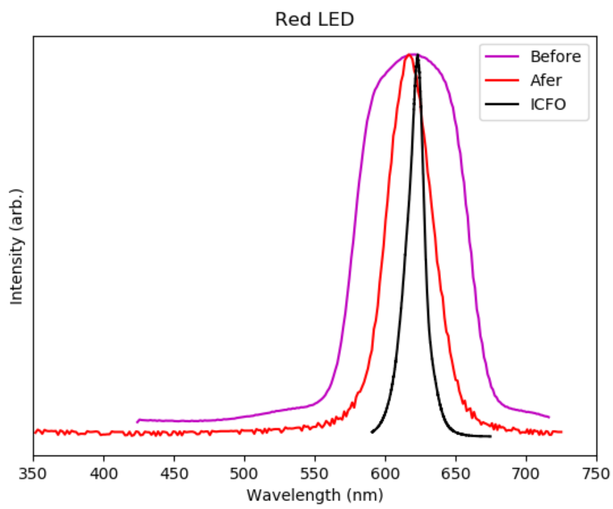

Figure 17: Comparison between the results obtained before adding the *collimation improvements*, after adding them and with the professional spectrometer.

In the figure above, three different measurements of the same Red LED are plotted. The magenta one represents the spectrometry obtained with the homemade spectrometer before implementing *Collimation Improvements*, the red one is the spectrum obtained with the same spectrometer after implementing them - which is the same spectrum represented in Figure 16. The black plot represents the spectrum measured with the ICFO spectrometer, used as reference (this is also plotted above). It can be observed how bad collimation makes the spectrometry wider. The wider one, with the worst collimation, is also much more rounded, because there is much more noise - of uncollimated light - near the peak; so, in this case, it can even be hard to find the real peak of the shape. We can conclude that the changes applied to improve collimation were effective, although the perfect collimation was not achieved - reference spectra are much thinner.

3.1.2 White LED

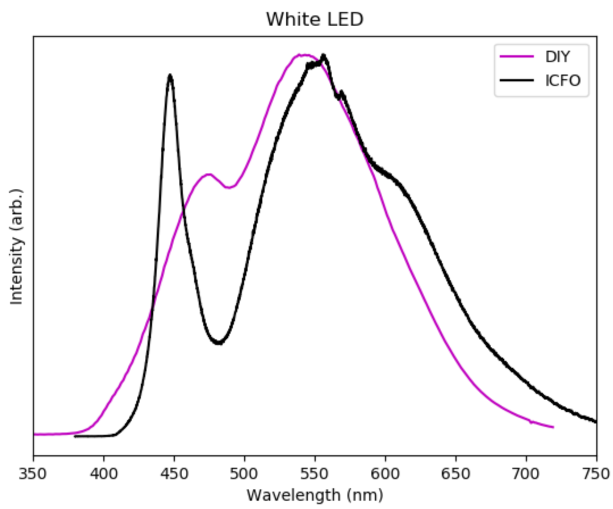

Figure 18: Spectrum of the White LED obtained with the DIY spectrometer (magenta) compared to the spectrum of the same LED obtained with a professional spectrometer (black).

The analysis of the white LED can be observed above - Figure 18. It can be seen how, more or less, the homemade spectrometer's spectrum draws a similar shape to the spectrum obtained with the professional spectrometer. However, it is much more different that how the colored LEDs spectra were compared with the professional ones. The two peaks are present, but both are displaced and the one around 450 nm - 500 nm has much less intensity.

The most intense peak of the homemade spectrometer result is located at 543.2 nm while the same peak of the professional result is at 555.700 nm. That is a difference of 12.5 nm, which is big but similar to the red LED difference. However, the other peak, in the homemade results appears at 473.4 nm, but in the professional spectrometry is located at 447.3 nm. In this case, the difference is of 26.1 nm, which is really big; too big. As said before, this is most probably caused by an error in wavelength calculus and it can be observed again how the displacement of the peaks goes to the middle. It is also true that spectrometers such as the one used as reference loose precision when measuring a big range of wavelengths, but it cannot cause an error of 30 nm. It can be confirmed regarding at Figure 19, where we can see that the peaks coincide with the blue LED and green LED peaks, so probably those LEDs are like the white LED with a filter.

Moreover the displacement of the lower wavelength peak, it has much more intensity compared to the other peak - oppositely to the reference spectrum - and the trough after it is much smaller. The lower intensity could be attributed to the spectral responsivity of the sensor[10], which has less responsivity at lower wavelengths than at higher wavelengths of visible light. The small trough is most probably caused by the uncollimated light. Although the sensor should not receive almost any light at that wavelength and there is not light of that wavelength, uncollimated light of other wavelengths reaches the sensor and makes it read a high intensity. This affects a lot to this trough because it is located between two zones with a lot of light, so there is more uncollimated light to reach the sensor there.

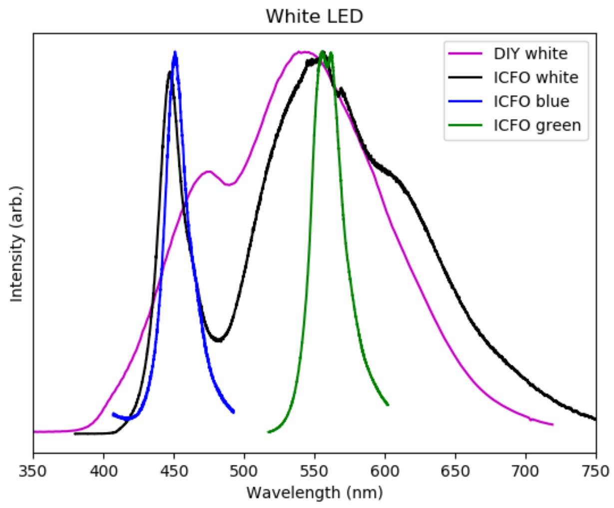

Figure 19: Blue and green LEDs wavelength peaks coincide with the white LED ones. If those LEDs are the same with some filters, the spectrometer did not loose precision.

3.1.3 Incandescent Bulb

This light source was an incandescent bulb powered with 220 V whose datasheet could not be found.

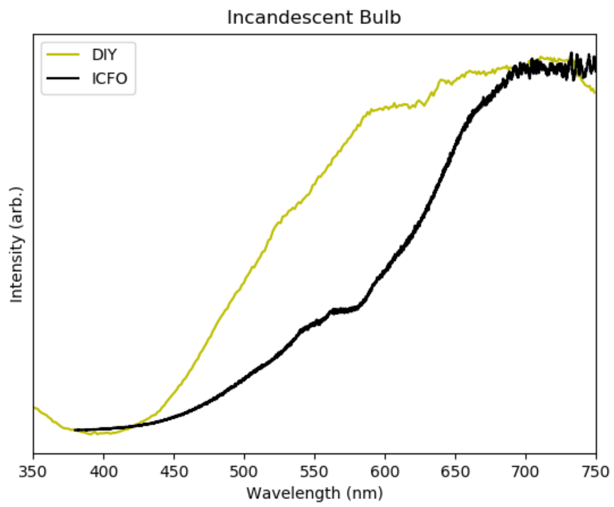

Figure 20: Light bulb spectra measured with this paper's spectrometer (yellow) and ICFO's professional spectrometer (black).

Although the spectra do not draw exactly the same graph, again, it is possible to recognize some similitudes in their shapes. First of all, it is easy to see how both spectra are constantly increasing - incandescent light bulbs emit more higher wavelength light. The same accidents can be observed in both spectra, as shown in Figure 21:

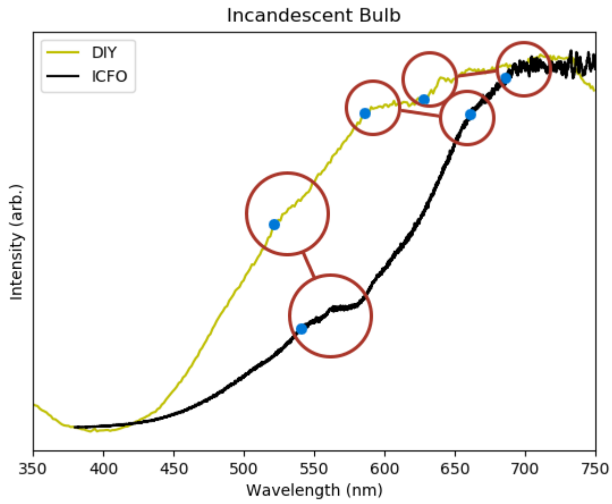

Figure 21: Connected circumferences show the same accidents on both spectra. Blue dots indicate same points that are compared below.

Between 500 nm and 600 nm a change in the increasing rate can be observed. In our spectrum, this change is located at approximately 520 nm while it is at 540 nm in the reference spectrum.

The next important change - marked with blue dots too - is located at 590 nm in the homemade spectrometry while at 660 nm in the reference one.

The last compared point is found at 630 nm in this paper's spectrometer measurement and at 680 nm in the ICFO's spectrometer measurement.

The displacements found are really high. The first one is separated by 20 nm, that is a big separation but the other ones are even more displaced: about 70 nm and 60 nm respectively. In this case, it is very difficult to think that those displacements are caused by wrong wavelength calculus, they are too big. Here the problem has more probably to do with collimation and diffraction. A light bulb did not emit just like a dot of light like the LEDs, because it is a shinning filament, if it was not perfectly positioned in front of the lens, the sensor could be reading light from other wavelengths where it should not be.

Moreover, although those shapes indicated in Figure 21 can be perfectly recognized, they show much smoother in the homemade spectrum. This has to do with the not perfect collimation again. This noise of uncollimated light, covers the troughs and makes them harder to be seen. It could also be the cause of the intensity difference from 450 nm to 650 nm, as it is more present near higher intensities, accentuating them.

3.1.4 Green Laser

This was the last light source analyzed with the spectrometer. Although its datasheet could not be found, it was written on it that its wavelength was of 532 nm with an error of ± 10 nm.

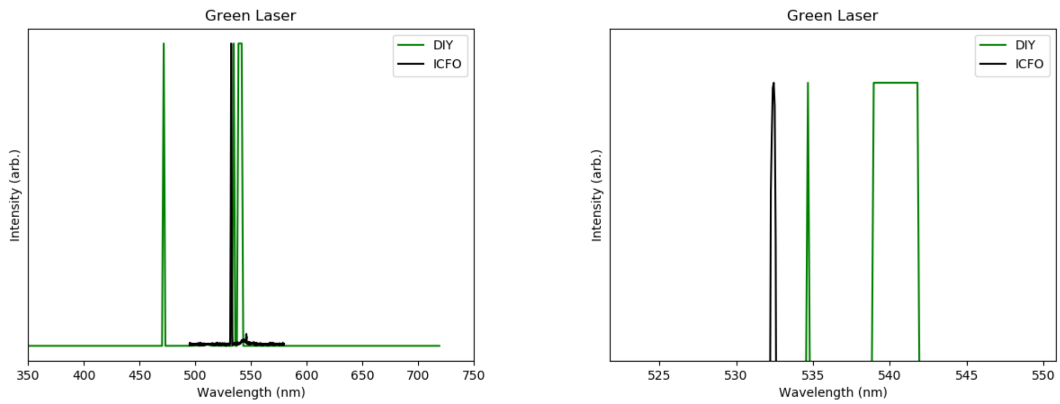

Figure 22: Green laser spectrum measured with the homemade spectrometer and with a professional spectrometer plotted together. First graph shows the whole spectrum and the second one just shows the top of the peaks between 525 nm and 550 nm.

The green laser spectrum was the most accurate spectrum obtained according to the reference one. The peak obtained with the homemade spectrometer - located at 534.7 nm - was only displaced 2.3 nm from the reference peak - located at 532.447 nm. Having the lowest displacement could be caused by being near the central wavelengths, as we observed the displacements tended to them - and this too.

The shapes of both spectra are exactly the same, too. That is for a very simple reason: lasers are monochromatic. This means that all light they emit has the same wavelength, so the shape consists in just one very thin peak. And, although the shape could have been deformed by the collimation issues, it was not because of another laser property: its light is already collimated - that is why lasers emit just one straight beam of light. In fact, the lens would not have been needed in this case.

The only problem that can be observed is that there are more than one peak, and it has been just said that lasers are monochromatic. This must have been caused by the light beams being reflected by the collimation aids mentioned before. Although painting them mate black to absorb as much light as possible, the laser beam was so strong that was reflected and reached the sensor although it was not in the angle of its wavelength. This light is so intense that, even configuring the sensor with the lowest gain mode and lowest integration time, the reflected beam reached its top value. The immediate peak after the correct one could not be a reflection of the wall, but probably was a reflection of some other part of the TSL2591.

3.2 Technical Specifications

After studying the results, some technical specifications could have been deducted. They are displayed in the next page. Resolution and precision are commented.

Voltage supply	4.5 - 5 V
Power up time	≈ 1s
Detector	TSL2591
Dynamic range	600M:1
Analog gain	1x
	25x
	428x
	9876x
Integration time	100 - 600 ms
Interface	Printer, microUSB
Grating	1000 lines/mm
Spectral range	200 - 750 nm
Temperature	-30 to 70°C
Resolution	≈ 1.4 nm
Precision	± 30 nm

3.2.1 Resolution

As the function used to calculate wavelength after each step included a sinus, there is not a constant resolution. There is less resolution at lower wavelengths and more resolution at the higher ones. At the beginning, each step supposes a bigger difference in wavelength that at the end.

For the reason mentioned above, the resolution has been defined as the arithmetic average of difference between each wavelength from 350 to 750 nm, as it was the range measured. With the help of Python, the resolution was obtained: 1.379 nm (≈ 1.4 nm).

3.2.2 Precision

It is difficult to determine the precision of the spectrometer, as it was very variable through all the measurements. Better precision was obtained when measuring light sources with a smaller range of wavelengths (color light) and near the central wavelengths - as it has been seen how the displacements tend to the center of the graphs. Supposing that the imprecision in the incandescent bulb spectrum was caused by a diffraction issue - not placing the bulb correctly -, so it was an user's mistake, the higher imprecision is found in the white LED spectrum.

Although most displacements are lower than 15 nm, one peak of the white LED spectrum is displaced 26 nm, for that reason the error of the spectrometer should have to be set at ± 30 nm, which is really high.

4 FUTURE WORK

After analyzing the results of the spectrometer and finding its weakest points and the features that should be improved, two ways of improving the experiment are shown below. The first one consists in some improvements that could be implemented in the already built experiment. The presents a completely redesigned spectrometer considering the mistakes in the original spectrometer's design.

4.1 Improvement Methods

In this section some improvements that could be applied to the spectrometer are presented, either to solve existing problems or to increase the efficiency of yet working processes.

4.1.1 Resolution

As the stepper can not do a step more little than 1/200 of a revolution, other elements included in the wavelength calculus could be changed in order to improve resolution - so to read more wavelengths in a specific range.

The easiest way to achieve that would be to make the rotating arm longer, so each step will cover the same linear distance but the angle - what is important for the wavelength calculus - would get reduced. The sensor would not necessarily have to further, just the wheel.

The wheel radius could also be reduced. The same angle of the wheel rotation would cover less linear distance, so the same step would suppose less angular distance. The problem is that changing the wheel would suppose adjusting all dimensions and, with the used stepper, it could never have a radius of less than 1.5 cm, because it measures 2.8 cm.

Finally, a different grating which spreaded light more, so each change in angle would suppose less change in wavelength.

4.1.2 Collimation

This is probably the biggest issue of this spectrometer. The proper way to solve it would be to use a good collimating set of lenses, but that would be very expensive .

A less effective but cheaper way would be to improve those collimation aids installed. Instead of using two panels to reduce the arm width, something like in the picture below could be used:

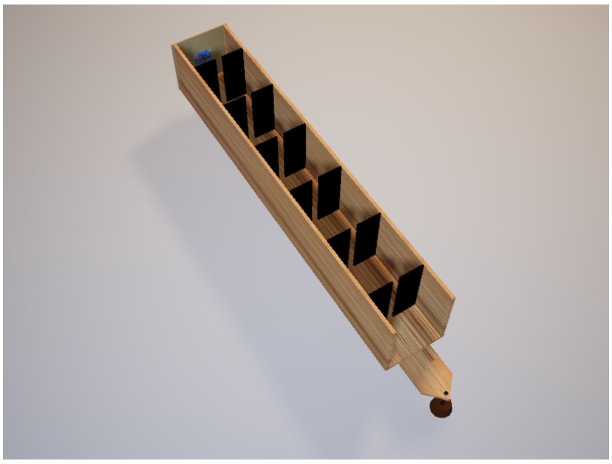

Figure 23: Panels separated by the width of the sensor and perpendicular to the arm would help to improve collimation.

Setting the panels this way would prevent light from being reflected and reaching the sensor, as the reflected light would go in other directions. To improve it to the maximum, the ideal separation between two side-by-side panels would be the width of the sensor - not the whole TSL2591, just its photodiode. The problem with this system is that would be very difficult to build without help of, for example, a 3D printer and that it would reduce the quality of the resultant spectra. The reason of this is that this method blocks uncollimated light, so there would be much less light reaching the sensor. Using a proper collimating system of lenses would make all the light reach the sensor, but to do so where it is supposed to do by its wavelength.

4.1.3 Precision

This is very important too, as some wavelength errors were unacceptable. As said before, the lack of precision can be caused either by issues in the stepper movement or by a bad wavelength calculus. Some experiments would be needed to discover whether it is caused by the stepper, by the calculus or both.

An irregular movement of the stepper would cause reading higher wavelengths than the calculated at some moments and lower at some others. To make the movement more regular improving the grip of the wheel would help. This could be achieved by using anti-slip materials for the wheel, such as rubber, but in the floor too and trying to reduce the maximum the grip of the two round ended screws - maybe using some sort of wheels. It could be tried too to remove that delay second between steps to make a constant smooth movement, but this could lead to timing problems.

To solve calculus problems, it would be very helpful to have some sort of calibration light. The reference spectra of the ICFO spectrometer could be used too. Instead of measuring the angle with a protractor, that is very inexact, the wavelength peaks of those spectra could be used to calibrate the spectrometer.

4.1.4 Reflection

Reflection of light against the sides of the arm, causes light of a different wavelength than the being measured to reach the sensor, modifying the results.

To prevent reflection a system like the presented in Figure 23 would be effective but, again, it would be difficult to apply it to a real model.

In case of the laser, which is the one where this phenomenon is most obvious; it could help to reduce the intensity of the laser, so the beam of light reflected would be much less intense than the one reaching them directly. In the laser spectra both beams had the same intensity because its intensity is higher than the maximum value the sensor can read. To reduce intensity, it could be a great idea to reflect the beam of light before entering the spectrometer. To do so a non totally reflective material would be needed, that could be glass or transparent plastic, for example.

4.2 Spectrometer Redesign

A new design of a DIY spectrometer is shown and explained below. This new version has been designed taking into account the weakest points of the main spectrometer of this paper with the intention of solving them and improving many other parts. However, this redesigned spectrometer would cost approximately the same than the original one. It has been designed to be contained in a box, so it would be portable, less fragile and, depending on the light source, capable of making measurements with ambient light.

To properly design the new spectrometer considering all the dimensions and specifications of its parts, a 3D model of it has been built. It is shown in Figure 24. Most of the main parts of the new design are the same as the ones used in the original spectrometer. The main differences are the use of a reflective diffraction grating - that requires the gear set - and the implementation of a monocular to prevent collimation problems.

The most important feature of this new spectrometer is the reflective diffraction grating. Using a reflective diffraction grating instead of a transmission diffraction grating - a transmission one is used in the original spectrometer - allows substituting the translational movement of the sensor with a rotational movement of the diffraction grating to read different wavelengths. Rotating the diffraction grating changes the direction of the reflected beam and the wavelength of the beams that reach the sensor. This method allows the spectrometer to have a much smaller size and to be stored in a box. Moreover, the accuracy of the wavelength calculation would increase a lot, as the angle would be exactly known because it would not depend on the grip of the wheel.

The problem of reflective diffraction gratings is that they are generally more expensive than transmission diffraction gratings. A possible solution would be using a diffraction

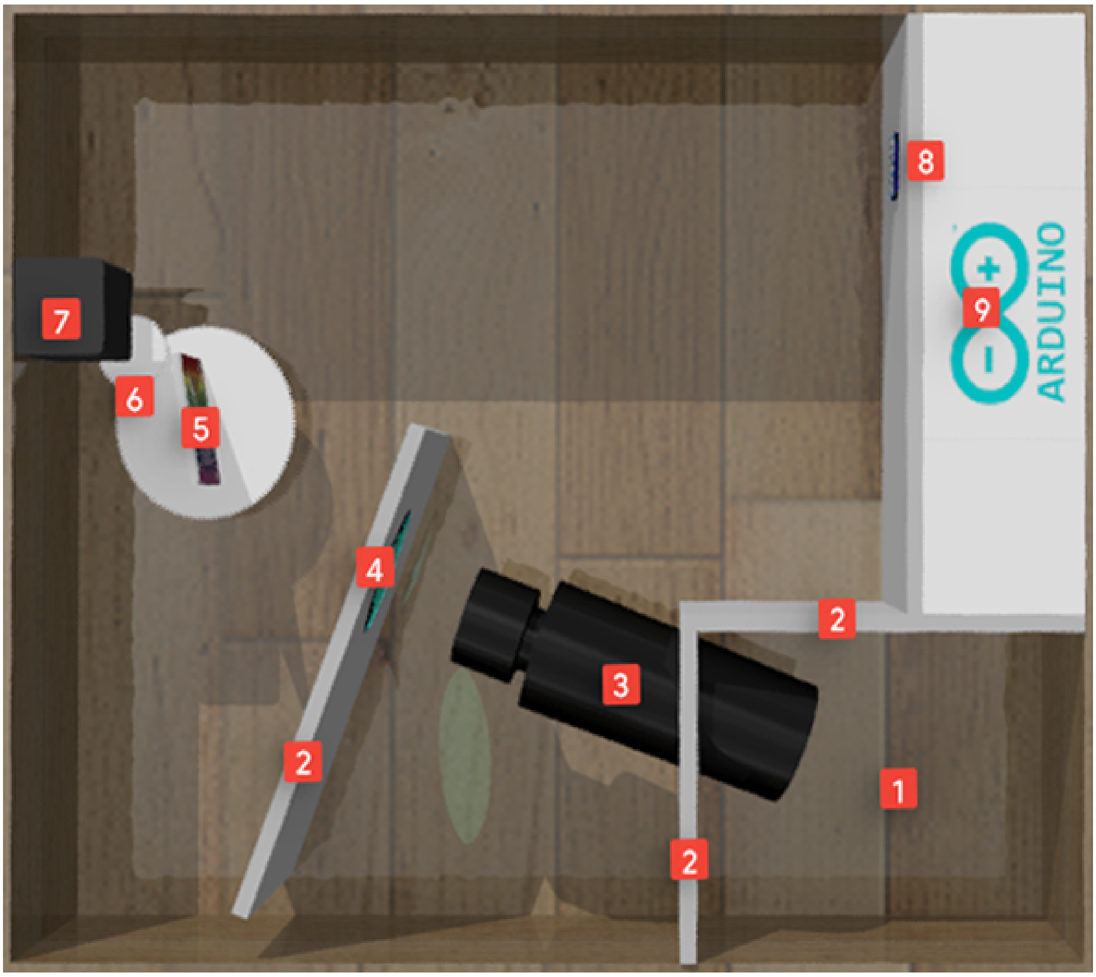

Figure 24: 3D model of the redesigned spectrometer. It has (1) a light source chamber, (2) some separators, (3) a monocular, (4) a lens, (5) a reflective diffracion grating, (6) a gear set, (7) a stepper motor, (8) a light sensor and (9) an Arduino board.

grating with a mirror on its back. A first surface mirror could be used not to lose quality. First surface mirrors do not have an acrylic transparent layer on its surface as most mirrors do. Atlhough these mirrors are also expensive, there are some cheap methods to remove the extra layer at home.

However, the diffraction grating cannot be connected directly to a stepper motor, as the resolution achieved by a normal - cheap - stepper motor would be too poor. The stepper motor used in the original spectrometer - which would probably be used to build this too - could perform 200 steps per revolution, that means steps of 1.8°. Moreover, rotating the diffraction grating would mean that the reflected beam is moved 3.6°. Knowing this and using the formula to calculate wavelength - explained in section 1 - we can deduce that the resolution around 30° (500nm) would be of 53nm:

$$1000sin(33.6) - 1000sin(30) = 53.39nm \tag{4}$$

To achieve the resolution of the original spectrometer - in which the sensor moved 0.097° each step -, a gear system would be used. Using some gears, the diffraction grating would turn much less than the spectrometer for each step. The minumum gear ratio to accomplish steps of 0.097° would be

$$3.6 : 0.097 \approx 37 : 1.$$

The monocular would also suppose a great improvement of the spectrometer. If light from a light source goes through a monocular towards where we would normally place our eye to see, the output light would have the same shape regardless the position and movement of the light source, it only changes its intensity. This means that the light source would not need to be specifically placed in any position to be properly focused for its measurement. With the monocular and some simple lens, it could be perfectly focused, avoiding collimation problems.

Although it is not shown in the 3D model - otherwise it would be too confusing -, all the inner sides of the box and the separators would be covered with black felt. It would be used to prevent reflection of light beams inside the spectrometer. As it is black, it absorbs most of the beams that reach it. Moreover, its texture prevents light to rebound as a single beam, and it dissipates it.

Separators would prevent light from reaching places it should not. This way, only collimated light would be able to reach the lens and only focused light would reach the diffraction grating and the sensor.

The Arduino board would be placed inside its own compartment so its lights - small informative LEDs that cannnot be turned of - would not affect the measurements. The sensor (TSL2591) - the same as the one used in the original spectrometer - would be placed on the separator of this compartment to make the wire connections easy. The box would have two USB outlets, the first one to connect the computer to the Arduino board and the other one to power the stepper motor.

To control this spectrometer, the same code used in the other spectrometer could be used and just some minor changes would be needed. The ratio of angle moved per step would be changed in the wavelength calculation and, as the Arduino board wold be inaccessible, the functions of the buttons would be removed.

5 CONCLUSIONS

It has been obtained a homemade spectrometer for 60.18 € (components cost can be consulted in the materials list at the end of the paper).

Results show that it is a capable spectrometer, as spectra could be recognized against reference spectra. However, deeperly analyzing the results and extrapolating the technical specifications, precision (± 10 nm), along with the poor collimation effects, shows it is not good enough for its use at a professional level.

The new design of the spectrometer presented in Section 4.2 or applying the improvements suggested in Section 4.1 to this spectrometer could make it capable of being used in some amateur projects, as could give some approximate but reliable enough results.

The main application of this spectrometer could be educational: for school science projects and demonstrations. It is affordable for most schools and institutions and, as it is homemade, it could consist on a 'Making your own spectrometer' project.

However, we can say that the results are pretty good in relation with the spectrometers prices, considering that a professional spectrometer may cost more than 1000€[1].

[1] Data obtained from several spectrometer sellers' sites - such as `labotienda.com`, `mt.com`, `thorlabs.com`, `oceanoptics.com`...

6 REFERENCES

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[10] P. 8. URL: https://cdn-shop.adafruit.com/datasheets/TSL25911_Datasheet_EN_v1.pdf.

APPENDIX A MATERIALS LIST

MATERIALS LIST			
Component	**Qtty**	€[2]	**Details**
Arduino Genuino Uno	1	20	`https://store.arduino.cc/arduino-uno-rev3`
Stepper Motor	1	19.95	`https://www.pololu.com/product/1206`
Adafruit TSL2591	1	6.95	`https://cdn-shop.adafruit.com/datasheets/TSL25911_Datasheet_EN_v1.pdf`
5V micro USB transformer	1	2.01	From *Kanlep* Powerbank `https://axpol.com.pl/files/file_add/download/1954_v3557_manual.pdf`
Lens	1	≈ 1	35 mm Ø biconvex
Diffraction Grating Slide	1	0.99	*Rainbow Symphony* Linear 1000 lines/mm
Piezo 220 Ω resistor 10 kΩ resistor Push button L293D motor driver Breadboard Male headers Arduino wires	1 1 2 2 1 1 6 21	1.08 0.50 1 0.70 1.09 2.28 0.50 ≈ 1	From Arduino Starter Kit[3]
Female-male jumper wires	16	0.63	30 cm *Dupont* colored jumper wires
Sound wires	1	≈ 0.50	1 m double wire
Small screws	2	≈ 0	0.1 inch Ø, 2 inch long, star type
Round ended screws (Screw eyes)	2	≈ 0	4 cm long
Shoe box	1	≈ 0	28 cm x 20 cm x 10 cm, cardboard
Plastic cap	1	≈ 0	2 cm Ø, from plastic bottle
Ruber Band	1	≈ 0	2 cm Ø
Nail	1	≈ 0	2 cm long, 2 mm Ø
Shelf holder	1	≈ 0	1.5 cm Ø, 4 mm Ø hole
Cardboard		≈ 0	2 mm thick
Wood		≈ 0	3 mm thick
Total		**60.18**	

[2]Cost of the total quantity of each component. Reference prices taken from internet.

[3]All datasheets of Arduino Starter Kit components can be found at: `https://store.arduino.cc/genuino-starter-kit`