Webcam Based Malus Law Experiment

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Abstract

In this work we develop the experimental procedure to test the Malus law with the use of a webcam. The use of the webcam and the computer allow the students to visualize the measurements in real time and analyze qualitatively and quantitatively the behavior of the experimental measurements. The use of this method allows obtaining accurate results with an uncertainty of 0.68%.

Keywords: Light polarization, Malus's law, computer-based measurements.

Resumen

En este trabajo desarrollamos un procedimiento experimental para probar la ley de Malus con el uso de una camara web. El uso de la camara web y la computadora permite a los estudiantes visualizar las mediciones en tiempo real y y analizar cualitativa y cuantitativamente el comportamientio de las mediciones experimentales. El uso de este metodo nos permite obtener resultados con una incertidumbre de 0.68%.

Palabras clave: Polarización de la luz, Ley de Malus, Mediciones basadas en computadora.

I. INTRODUCTION

Measuring in engineering and science is the way to test the theoretical prediction of a physical phenomenon. In an undergraduate laboratory the results obtained in an experimental activity will enhance the well understanding of the physical concepts that describe the studied phenomenon, in this case we study polarization experimentally.

Polarization is a feature of electromagnetic waves that nowadays its technological application is increasing. Some devices that use this feature are the Liquid Crystal Displays (LCD), every laptop computer has one of this, in television projections the use of this feature is fundamental to achieve the effect of three-dimension scenes (3D TV), also as a daily use in telecommunications is a fundamental feature to have links to communicate wireless [1]. In science and engineering, there are a lot of applications for the polarization property of light: photo-elastic stress measurement, characterize minerals [2] imaging to enhance the visualization in microscopy [3, 4], to manage information in quantum physics [5] or to control the spin of micrometric particles with optical twisters. However, the understanding of the concepts in physics can be concreted with an experimental setup that focuses in the phenomena mainly, that foster the learning attitude in students for the physics and not in the technical experimental setup details.

Polarization is a physical feature of light that cannot be measured directly because the high frequency of light waves. A common experiment to proof the existence of polarization in light waves is to test the known Malus law. Experimentally it is common to construct a circuit with a photoresistor to measure the electrical current generated by light hitting the sensor as an indirect test of the Malus´s law. The photoresistor has an inconvenient non-linear light intensity response and that will lead the student to a misconception of the physical law. A webcam has quasi-linear response to intensity that allows performing the experiment in very accurate way.

Nowadays webcams become a cheap laboratory instrument for high precision measurements [6, 7]. In this work we develop the method to experiment the Malus law based on a webcam. The principal characteristic is to take pictures with controlled exposure time, in this case setting it as a constant in every snapshot and then calculate the average intensity in the captured image. Assuming the intensity varies only by the effect of polarizers the Malus law can be tested with a confidence of 99.32% in contrast with the 82.33% obtained when use the photoresistor to measure the electrical current produced by light. This resulting confidence is approximately equal to experiments done with a more expensive equipment [8].

This work is organized as follow; first a review of the Malus´s law is shown, followed by the analysis of obtained results with the photo-resistance experiment. Then the software and the webcam experiment are explained. And finally, the analysis of data obtained with this experiment is analyzed.

II. MALUS'S LAW

Randomly linear polarized light is composed of waves whose oscillation plane is arbitrary; the electric field associated to waves has a vector nature, that mean it can be decomposed in its vector components on any coordinate system.

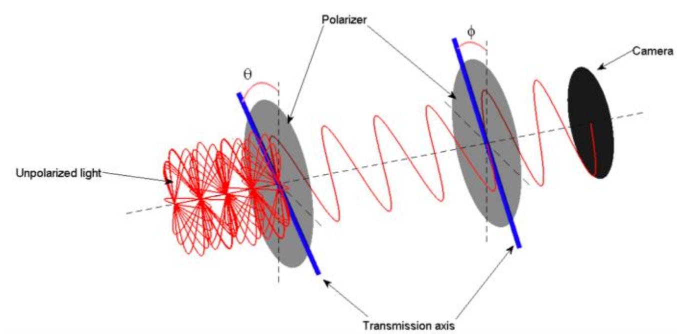

Figure 1. Scheme of the experimental setup of the Malus law.

A linear polarizer performs as a filter that allows passing part of the waves, the part that correspond to the vector component in direction of the polarizer transmission axes the other component is absorbed. The field after the first polarizer becomes

$$E = \mathrm{E}\, sin\,\theta\hat{\imath} + E\, cos\,\theta\hat{\jmath}, \qquad (1)$$

where θ the angle is the rotation angle of the transmission axis with respect a vertical line as shown in Figure 1. The wave represented by (1) continues traveling to reach a second linear polarizer whose transmission axis has a rotation angle φ, at this polarizer the same filtering effect occurs to have a final wave given by

$$E = \mathrm{E}\, cos(\theta - \phi)\, sin\,\phi\,\hat{\imath} + \mathrm{E}\, cos(\theta - \phi)\, cos\,\phi\,\hat{\jmath}. \qquad (2)$$

The wave described by (2) is detected measuring its intensity (electric field temporal average), this is given by

$$\mathrm{I} = \left|E\right|^2 = I_0\, cos^2(\theta - \phi), \qquad (3)$$

where I_o is the intensity I when θ = φ and represent the maximum intensity of the electric field that can pass through the whole system. The Malus experiment consists in the rotation of one polarizer and leaves the other at a constant angle. Eq (3) is known as the Malus Law that commonly is shown when φ = 0. A scheme of the Malus law setup is shown in Figure 1.

III. THE ELECTRIC EXPERIMENT

It is common that, students perform the experiment measuring the electrical current generated in a photoresistor by the incident final wave, as shown in the experimental setup in Figure 2. Figure 3 shows the resulting graph with data obtained from a student report. In this figure the data is compared with the expected values i.e. the $\cos^2(\theta)$ behavior showing a high amount of error. Figure 4 shows the plot of intensity versus $\cos^2(\theta)$ in order to have a linear analysis of the data, here is notable the nonlinear response of the photo-resistance to light intensity changes. The best fit line obtained with the experimental data has a correlation coefficient of r = 0.8233 the uncertainty of the slope was within 17.77% of unity. This huge uncertainty will produce a misunderstanding of the expected results of the experiment and maybe of the concept of polarization and the Malus law.

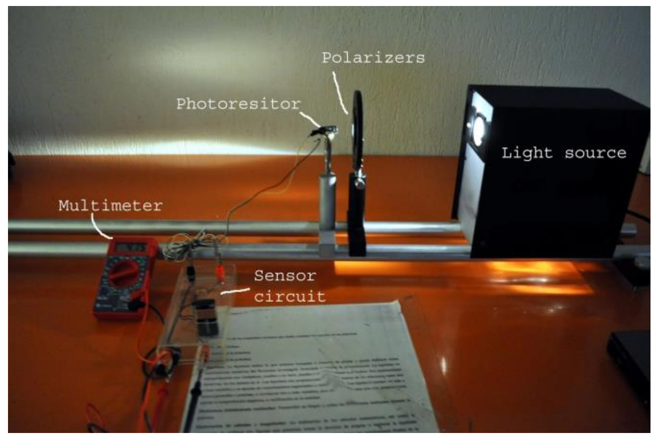

Figure 2. Experimental setup to measure the electrical current in the photoresistor.

IV. THE WEBCAM EXPERIMENT

For the webcam experiment we need some idea of how the digital image is constructed and can be manipulated. First, a digital camera has a rectangular array of sensors and every of them capture the light intensity, so we can make an analysis of intensity sensor by sensor or better pixel by pixel in the captured image. A camera will have millions of sensors and trying to analyze every one sensor will result in a huge amount of work and the results will not give us a good approximation of what happen with intensity in every sensor due the implicit (electronic) noise. Instead of thinking in a localized measurement of intensity we will measure the intensity in the entire surface of the sensor or the entire area of the digitalized image.

When capturing an image for the computer it is just an array of numbers, those numbers commonly run from 0 to 255 levels of intensity where 0 is completely dark and 255 is the maximum amount of intensity. That array of data can be manipulated just by doing arithmetic operations in this case we calculate the average intensity as a good indicative of the intensity level in the whole image.

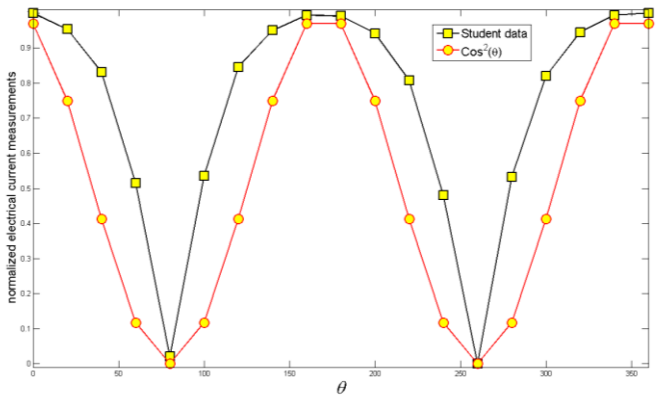

Figure 3. Plot of the data measured by a student with the photo-resistor, it shows a large difference between the theory and the experimental measurements.

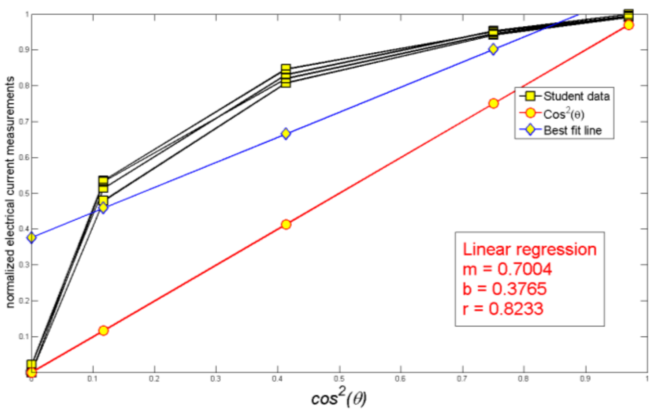

Figure 4. Linearized plot of the theory and experiment, correlation of the data quantify the uncertainty of the photo-resistor method, data shows a confidence of 82.33% of unity.

That is the method used in this work by calculating the average intensity in the image we measure intensity that arrives to the sensor, here we can get a problem, most of the webcam cameras has an auto-adjustment of any parameter that regulates the quantity of light that is captured to avoid the saturation of the image and the loss of detail of the objects in the image. Through software we can control the parameter of the camera (the availability of the parameters to control depends on the camera).

In order to not deviate the attention of the student with programming issues, we construct a Graphical User Interface (GUI, programmed in Matlab) to control the camera parameters in an easy way. Figure 5 show the GUI, it has four pop-up menus to select the desired characteristics for the camera to work, in this case control the exposure time is enough for this experiment. The GUI has two axis one to show a plot of the average intensity, the other is to show the captured image. It has two push-button one to capture an image, the other to clean the plotted data. The GUI shows the selected characteristics of the camera to work.

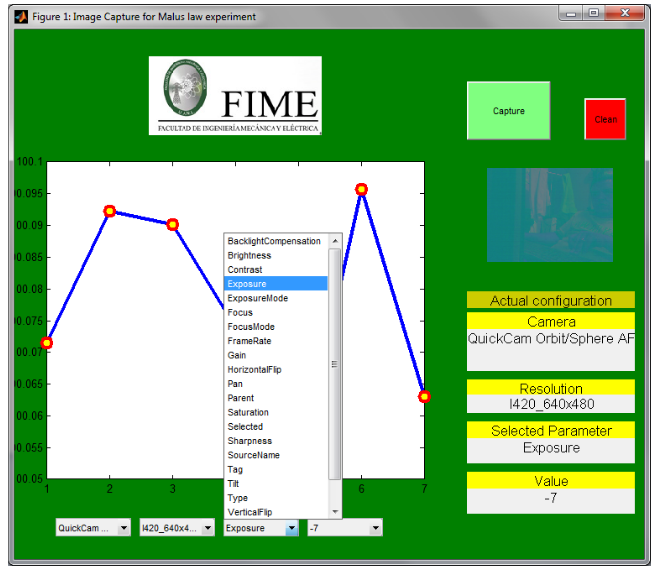

Figure 5. Graphical interface, showing one of the four pop-up menus that are used to control the camera parameter, in this case the exposure time. The green push-button (capture) the user can capture a picture and its intensity average is plotted in the left axis, every red circle is the average of one capture. Captured images are not saved to disk. Small axes in the right show the captured image. The red push-button (clean) are used to clean the plot, the yellow messages are used to show the information about the characteristics used with the camera.

Once the camera configuration is selected, the experiment consists in rotate the polarizer with a constant increment angle and in each rotation push the capture button to calculate the average intensity and plot it. An example of the experimental setup and its performance is shown in figure 6.

Figure 7 shows the plot of the intensity captured with the camera, the squared marker data is that obtained from the camera shots and the circle marker data is the theoretical graph normalized to the experimental data for a better fit between theory and experiment. Figure 7 shows the great appearance between theory and experiment. The linear analysis of results is shown in Figure 8 it shows a correlation of r = 0.9932 that mean a confidence in the slope of 99.32 percent of the unity. This confidence captures in high detail the Malus law behavior and gives the student an experimental experience that confirms the theoretical concepts about polarization of light.

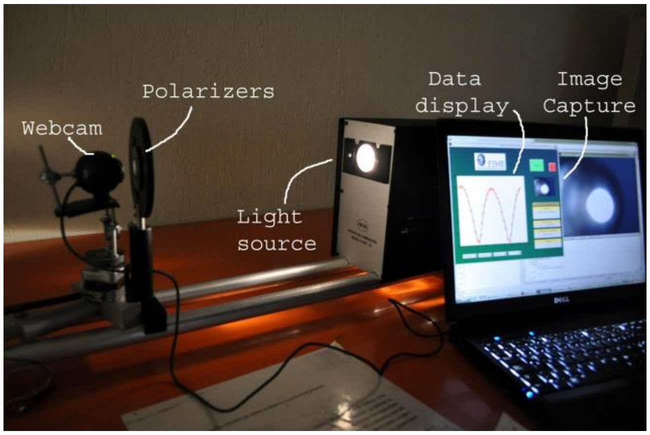

Figure 6. Experimental setup for the Malus law with a webcam.

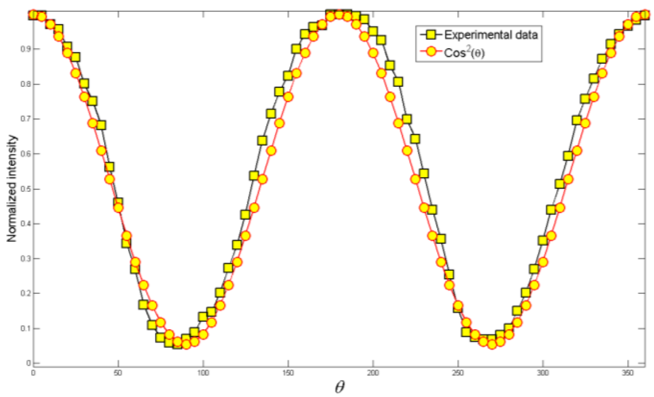

Figure 7. Typical experimental measurements of the intensity with the web-cam, it shows a high concordance with the theoretical expectative. The cos2(theta) has been adjusted to fit the max and minimum values of the experimental data.

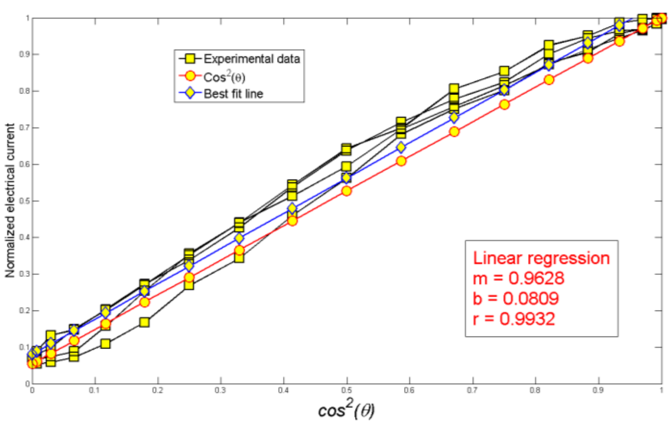

Figure 8. Linearized version of the experimental data shown in Fig. 5. Correlation of the theoretical vs. experimental data shows a confidence of the 99.32% of the unity.

V. CONCLUSIONS

We have developed a webcam-based technique to experiment with light polarization though the Malus Law, results show a high accuracy with respect the theory. We compare with the results obtained with the use of a photo-resistance that is the common way to do the experiment. The comparable results are that the uncertainty of the photo-resistance is 17.77% of the unity versus the 0.68% of the unity obtained with the webcam experiment. In this way we show an advantage in using the photographic technique developed in this work that can be implement in an easy and cheap way, nowadays a webcam with VGA (640x480 pixels) resolution is a common device everywhere.

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