Simple and automatic wavelength calculation with a machine vision camera, by measuring the diameter of an Airy disk

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ABSTRACT

This work presents a simple and automated educational resource with the aim of determining the wavelength of a laser source that uses the Airy disk generated by a circular aperture. It is known that there is a relationship between the diameter of the central disk and the distance between the circular aperture and the image plane. These two parameters are automatically measured by using a machine vision sensor and an ultrasonic distance sensor, respectively. This resource can be applied in graduate or undergraduate Physics and Engineering laboratories and classrooms for educational, demonstrative, or measuring purposes.

Keywords: Wavelength, Airy disk, automation, machine vision, educative resource.

1. INTRODUCTION

In order to know the wavelength of a source, some methods use optical setups based on measuring the fringe spacing produced by interference [1-3] or by counting the number of fringes [4]. Some others use the distance between the diffraction orders generated by a diffractive element such as a diffraction grating [5] or a ruler [6]. In this proposal, the estimation of the wavelength is based on the automatic measurement of the diffraction pattern generated by a circular aperture and its distance to the viewing screen, by using a machine vision sensor (Huskylens, an easy-to-use artificial intelligence camera/vision sensor with integrated functions such as face recognition, object tracking, object recognition, line tracking, color recognition, and QR code recognition) and an ultrasonic sensor, respectively.

An Airy pattern can be observed in the far field region at a distance R when a uniform beam of light is passed through a circular aperture of diameter d (Fraunhofer diffraction when R>>d). This pattern is formed by concentric disks, knowing the central disk as the Airy's disk, where approximately 84% of the received energy is concentrated.

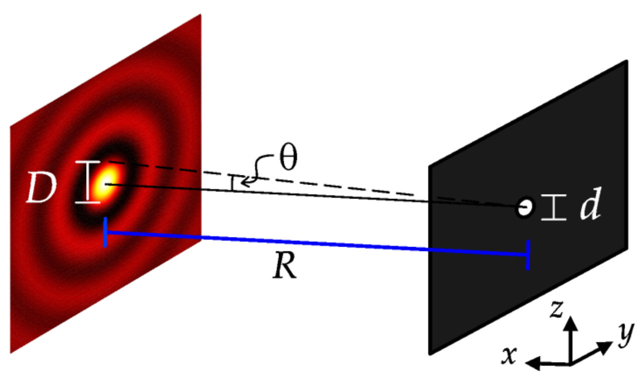


Figure 1. Airy pattern formed in far field by a circular aperture.

The relationship between the diameter of the central disk and the wavelength of the light source (λ) is given in the following equation

$$D = \frac{2.44\lambda R}{d} \quad . \tag{1}$$

From this equation, lambda can be solved to obtain the following expression

$$\lambda = \frac{dr}{1.22R} \quad , \tag{2}$$

where r is the radius of the Airy disk ($r = D/2$).

A method that uses the Airy disk diameter and the distance R to estimate λ has been proposed by Rivera-Ortega [7]. However, the present proposal presents a multidisciplinary and automatic method that involves optics, programming, electronics, and image analysis by using a machine vision sensor (Huskylens camera) that can encourage motivation and promote STEM skills in different areas by making, modifying or using the educational resource.

2. IMPLEMENTATION

The schematic of the experimental setup is shown in Figure 2. To obtain experimental results, an RGB laser diode module, a circular aperture of d =100um and a polarizer were used to prevent camera saturation. The diameter of the Airy disk and the distance between the observation screen (made with vellum paper) and the circular aperture were observed and sensed through the use of a machine vision camera and an ultrasonic sensor (HC-SR04), respectively. The electronic interface, programming and display of the results were carried out with a micro:bit board and an OLED display (HW-239A). In order to validate and compare the results, a Thunder Optics mini USB, 400-720nm spectrometer was also used.

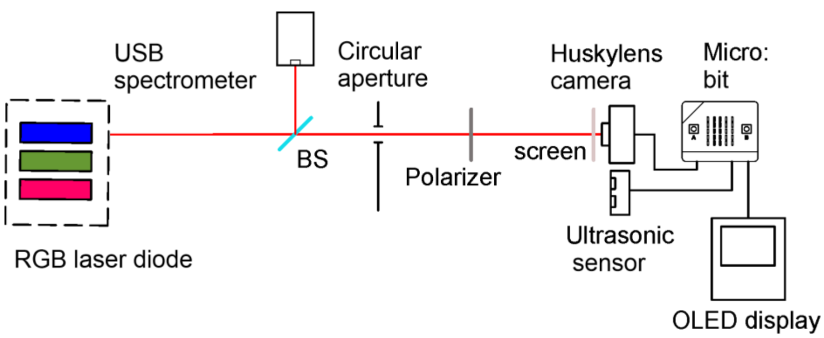


Figure 2. Schematic of the experimental setup.

A calibration stage is needed in the process to compute the measurements in spatial units (known as spatial calibration [8]). This is achieved by the color detection function included in the Huskylens camera. This function encloses a colored object with a rectangle, storing its width or height pixels value in a variable.

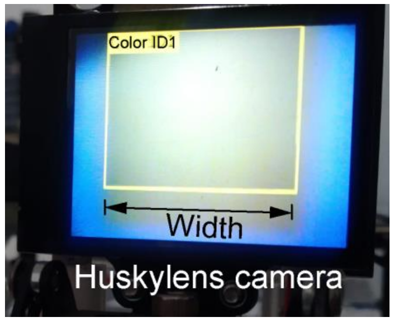


Figure 3. Calibration process by detecting the width of a yellow square.

For this calibration stage, a yellow square of 0.74 cm x 0.74 cm printed on vellum paper was used. In such a way that, taking into account the width of the detected square and the real size of the calibration object, the size of a pixel can be obtained using a simple rule of three

$$\begin{matrix} 0.74\text{cm} \rightarrow \text{width(px)} \\ x(\text{cm}) \rightarrow 1\text{px} \end{matrix} \quad ; \quad x = \frac{0.74\text{cm} \cdot 1\text{px}}{\text{width(px)}} \approx 0.0038\text{cm} . \tag{3}$$

The pixel size resulting from the calibration for this particular case is 1px=0.0038cm. This same color detection function was used to detect and determine the diameter of the Airy disk for a red, green and blue laser, respectively (Figure 4a-c)).

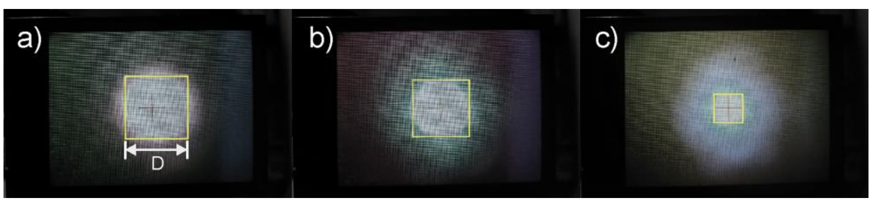


Figure 4. Detection of the Airy disk corresponding to a a) red, b) green and c) blue laser diode.

The distance R between the circular aperture and the screen can be determined by the ultrasonic sensor or it can be directly given in the micro:bit code. Finally, the wavelength is computed by using equation (2). The result of the calibration and the wavelength are shown in an OLED display.

Figure 5a) shows the calibration result displayed on the OLED screen, while Figure 5b-d) shows the Airy disk diameter as well as the estimated wavelength regarding to a red, green and blue laser diode, respectively

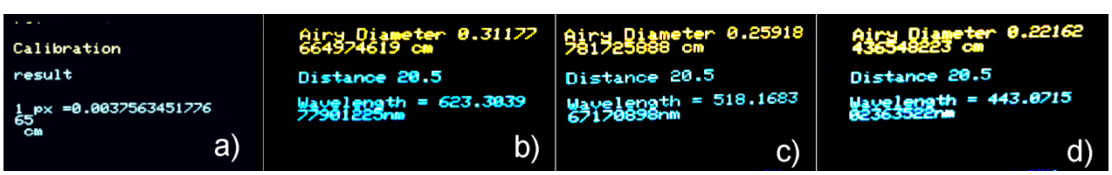
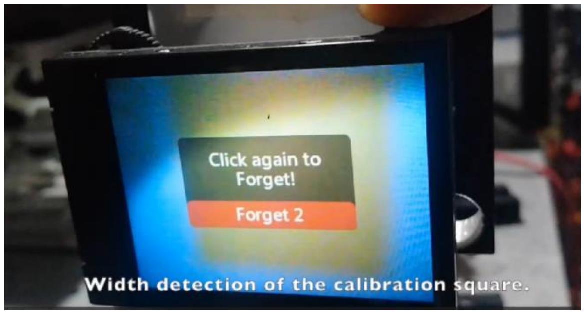


Figure 5. a) Calibration result, b-d) Airy disk diameter and wavelength for red, green and blue laser. Detection of the Airy disk corresponding to a a) red, b) green and c) blue laser diode.

The programming of the entire process was carried out using Makecode, which is a free open-access platform, based on block programming. In the following link you can download the code used for the implementation presented https://www.dropbox.com/scl/fi/kozmlsei3cg4myafxxlhp/microbit-Airy_dist_fixed_distance.hex?rlkey=ltagrpzu9ramrd97w9y5hj2u2&dl=0

The use and steps to use the tool proposed here can be seen in Video 1



Video1. A descriptive video with the steps to follow in order to calculate the wavelength of a laser source. http://dx.doi.org/10.1117/12.3023665

3. EXPERIMENTAL RESULTS

In order to verify the precision and repeatability of the process, 25 individual wavelength measurements were made with the RGB laser for different distances (R) between the observation plane and the circular aperture, taking the average of the measurements as the estimated wavelength ($\bar{\lambda}$) . The experimental distances are R= 20.5 cm, 29 cm, 25cm, 16.5 cm and 12.5 cm showing the corresponding results in Figure 6a-e), respectively.

a)	Airy diameter (D)	Estimated wavelength ($\bar{\lambda}$)	Reference wavelength	Error %
Red	0.31cm	623.30nm	635nm	1.84%
Green	0.26cm	518.17nm	521nm	0.54%
Blue	0.22cm	443.07nm	476nm	6.92%

b)	Airy diameter (D)	Estimated wavelength ($\bar{\lambda}$)	Reference wavelength	Error %
Red	0.45cm	632.83nm	635nm	0.34%
Green	0.36cm	514.84nm	521nm	1.18%
Blue	0.33cm	471.94nm	476nm	0.85%

c)	Airy diameter (D)	Estimated wavelength ($\bar{\lambda}$)	Reference wavelength	Error %
Red	0.38cm	624.14nm	635nm	1.71%
Green	0.31cm	515.07nm	521nm	1.14%
Blue	0.29cm	490.83nm	476nm	3.11%

d)	Airy diameter (D)	Estimated wavelength ($\bar{\lambda}$)	Reference wavelength	Error %
Red	0.25cm	618.84nm	635nm	2.54%
Green	0.22cm	526.47nm	521nm	1.05%
Blue	0.19cm	471.06nm	476nm	1.04%

e)	Airy diameter (D)	Estimated wavelength ($\bar{\lambda}$)	Reference wavelength	Error %
Red	0.19cm	632.42nm	635nm	0.41%
Green	0.16cm	517.44nm	521nm	0.68%
Blue	0.14cm	471.44nm	476nm	0.96%

Figure 6. Experimental results for distances a) R= 20.5 cm, b) 29 cm, c) 25cm, d) 16.5 cm and e) 12.5 cm

4. CONCLUSIONS

It has been presented an automated and simple method to estimate the wavelength of a laser source using the Fraunhofer diffraction phenomenon resulting from a circular aperture by measuring the diameter of an Airy disk, using the color recognition mode of a machine vision sensor and by measuring the distance (manually or automatically) between the aperture and the viewing screen; offering a reliable, educational, and even measurement resource without the use of optical devices and apparatus commonly found in physics or optics laboratories. This proposal can also be implemented in any non-isolated surface. The main error sources presented are due to the ultrasonic distance sensor and to the width of the square detected in the calibration stage. However, this proposal gives an acceptable approximation, being perfectly suitable to be applied for didactic, educational, demonstrative, and even measurement purposes in topics that involve optical phenomena and concepts such as diffraction and wavelength for undergraduate or graduate students in the field of Physics and/or Engineering.

This automated method to estimate the wavelength of a laser source has been used in physics classrooms and laboratories as a teaching/learning tool to introduce or reinforce physical concepts such as wavelength, diffraction pattern generated by a circular aperture, and image processing, to name a few (taking into account that sometimes these concepts are not addressed experimentally due to the high costs of measuring devices, as well as the fact that some schools do not have laboratories for these purposes). However, because knowledge such as optics, programming, and electronics was involved, interest was shown by students who were not necessarily interested in physics, also stimulating team and collaborative work.

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