Design and manufacture of a mechanical system for teaching the diffraction phenomenon

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Abstract. This article describes the design and manufacture of an accessible and easy-to-use mechanical system as a teaching tool to learn the light diffraction phenomenon. The teaching tool was designed by modules and manufactured piece-piece in 3D printer technique. It was made in a polymer with a relatively low cost. This mechanical system facilitates that both teachers and students improve the teaching-learning processes. The didactic system is more reliable because it facilitates the verification of the diffraction theory in the Fraunhofer regime and in turn allows to study the decomposition of the white light of a fluorescent bulb in the different colors that compose it using diffraction gratings. This tool is supported with a mobile application of free and interactive access, in which teacher and students can check the results of the experiments. The diffraction patterns achieved through this mechanical system can eliminate the use of high-cost equipment that generally limits some of the experiments that take place in a physics course.

1. Introduction
The diffraction is one of the main optics topics. It is generally introduced in regular and specialized courses of fundamental physics at universities and even in some schools in their last chapters. Diffraction is a wave characteristic phenomenon that occurs when a wave front passes through an obstacle or an opening that gets in its way. The openings behave as secondary sources of light and the optical disturbance beyond the obstacle can be studied from the interference phenomenon [1]. Diffraction is considered one of the most interesting phenomena in physics because of its prominent role in the explanation of light nature. Diffraction also originated a paradigm change between geometric optics and wave optics. Today, this change of paradigm is still complicated to understand for some students. Therefore, certain authors suggest using some didactic tools that allow to properly construct the diffraction concept.

On the other hand, the technological mediation based on TICs is one of the most important tools used to improve the quality of education and constitutes one of the updated trends for the improvement of teaching and learning processes in all areas of the science [2,3]. In that sense, physics in its eagerness to seek explanations for the nature of everyday phenomena, requires tools that allow building the concepts using simple elements in a laboratory, among which are highlighted: the development of the Apps, the didactic software and the experimental tools, as reported by some authors [4,5]. Generally, the process of teaching and learning in physics are held through experimental tools in laboratories. These technologies are generally expensive and difficult to access. The development of the Apps and the didactic software constitute an economic tool that could improve the
learning of the students. In this sense, different authors highlight the possible use of smartphones and applications as part of a didactic strategy for the teaching of diverse physical phenomena. One of the best ways to build a concept or explain a phenomenon in optics is by using the laboratory [6,7]. These practices are supported with specific elements such as mirrors, light sources, beam splitters, optical banks, lenses, etc. Today, the printing of certain types of elements such as optical banks and supports in general could reduce the costs for the development of the experiments if they are manufactured through a 3D printer. 3D printing is considered a new emerging technology which diffusion and reduction of costs has led to its use in teaching in different areas of knowledge [8]. Specifically, in the area of optics, demonstration kits have been developed to facilitate the teaching of the concept of diffraction and interference based on the selection of wavelength provided by a diffraction grating whose elements were printed using a 3D printer [9,10], in the same way, teaching educational projects have been developed for the understanding of mathematical concepts using 3D printing [11].

In this work, we report the design and manufacture of a didactic tool in the form of an optical bank made by 3D printing. This device is useful to teach the phenomenon of diffraction. The didactic system is a modular system that has been designed using CAD computer-aided design software and was manufactured piece by piece with a 3D printer. Then, a modular mechanical system was designed as a mechanical positioning system to facilitate the replacing an updating of pieces that compound the device. The design was complemented by the use of a mobile application “Teaching diffraction” Apps to facilitate calculation and prediction of results. It is also used to enhance the apprehension of the concepts of diffraction phenomenon by the students at different levels of education.

In the development of the investigation, design and manufacture of a modular system was made piece by piece using a 3D printer. This is a novel way of designing and manufacturing low-cost didactic elements that allow the development of modular structures for teaching in different areas of science. The printing of the pieces of the optical bank and its modular construction allow to improve many of the discomforts during the measurement process, for its adaptability to fix and adjust all optical devices and measuring instruments with great precision; characteristics that are important in the measurement processes in optical experiments.

2. Method of design and procedure

The teaching-learning system of the sciences specifically in physics is one of the great weaknesses of actual education process. The access of teachers to didactic tools is necessary to develop classes with sufficient dynamism for the construction of knowledge and the systematization of information. This way didactic tools allows the student to select and organize the relevant information and integrate it in a coherent and articulated way. The education process also includes technological challenges related with the objective of achieving a significant and critical learning according to methodologies such as solving problems. Some authors in general, suggest that using elements of visual support to understand in a precise and simple way the topic that is being developed. In this sense, the manufacture of teaching materials and the development of experiments for teaching are tools to support the teacher to improve student learning. According to this and taking into account the different difficulties presented for the development of experiments in physics.

In this investigation, difficulties of some of the traditional experiments that are carried out in the optical courses and specifically on the difficulties that result from the limitation of the equipment used for the development of the experiments are considered.

The phenomenon of diffraction of light was selected in this research for its relevance in important experiments in classical physics. The manufactured teaching system was designed by modules, piece by piece, using the computer-aided design software SolidWorks 2016 SP3.0. In the design, it was possible to consider the interconnections between modules of each one of the mechanical components that are part of the didactic system, the measuring instruments and in general, with any other external device that can adapt to the system.
3. Experimental design
A commercial 3D printer XYZ PRINTIG da Vinci 1.0A was used for the manufacturing of the pieces with ABS polymer which was selected for its low cost. The computer-aided design program SolidWorks 2016 SP3.0 was used for the design of gears, toothed rules and gear mechanisms as shown in Figure 1, which make possible the movements by means of the equation of the toothed module of gears [12], given by the Equation (1):

\[
\frac{d}{z} = \frac{p}{\pi} = m
\]  

(1)

where \(d\) is the primitive diameter, \(z\) is the number of teeth, \(p\) is the step or circular distance between the teeth and \(m\) is the gear module. In this case, a module of 0.8 was selected with 30 teeth, calculating a primitive diameter of 24 mm and a step of the gear or displacement of the serrated ruler of 2.51 mm. The latter determined a precision of 2.51 mm of movement in all the designed systems, later, once the pieces were printed. They were adapted and assembled by using screws, obtaining the prototype shown in Figure 2.

![Figure 1.](image1.png)

(a) Rotation and translation modules, (b) Static modules for positioning.

![Figure 2.](image2.png)

(a) 3D model of mechanical system designed, (b) Mechanical system printed and implemented.
The mobile application was designed and programmed using the App Inventor platform of the Massachusetts Institute of Technology (MIT), this application displays three buttons that allow access to a summary of the diffraction history, the assembly instructions and the third button to check your results. The main interface of this application is shown in Figure 3(b). In the option “Check your results”, the user enters a sub-menu, in which the experiment can be selected. It is clear that the user can choose between three options: a single slit, a circular slit and diffraction grating. The application can be used with other types of diffraction gratings that are used in demonstration experiments with low cost elements, such as DVDs and CDs. In Figure 3, the main interface of the App developed is observed:

![Figure 3. (a) Start interface (b) Main menu interface of the application for teaching the diffraction phenomenon, (c) Interface sub-menu selection of the experiment, (d) Interface for the calculation of the diameter of a circular slit.](image)

4. Results
Several experiments were developed to test the experimental setup observed in Figure 2(b) and the App observed in Figure 3. Where the aim is to verify the effectiveness of the tool to predict experimental results such as: the ability to determine or calculate the width of a single rectangular slit, the diameter of a circular slit, the spatial distribution of a series of rectangular slits located in a diffraction grating, the checking of the emission lengths of pure light sources and some other experiments from measurable experimental data, such as, the wavelength of a light beam emitted by a point source of monochromatic light, the distance of separation between the diffraction slit and the observation plane and by last, the distance between the first central maximum of intensity and the second central maximum of intensity. It was possible to use the device for the spectral characterization of light sources and the verification of the diffraction phenomenon using different apertures. It was necessary to make the measurements using a technique of analysis and treatment of images that allows to obtain a relationship between the pixels of the images obtained and the physical distances to determine the distance between the first central maximum of intensity and the second central maximum of intensity. For this, it was necessary to make a code in MatLab that allowed to capture the image of the diffraction patterns to obtain the approximate lengths.

The elements necessary to perform the experimental assemblies are a low-cost microscope reticle, a Helio-Neon laser that can be replaced by low cost commercial pointer, a digital camera with CCD sensor with variable lens that can be replaced by a low-cost camera and an observation screen with a white sheet of paper. All these elements will allow us to achieve images of the diffraction patterns to perform the calculations of distances between points in the image. Subsequently, for the analysis of the given phenomena, the results of the diffraction theory in the far-field diffraction regime are used
and it is possible to relate the distances with the wavelength of the light source using some simple geometric expressions, given by the Equation (2) to Equation (4).

\[ b = \frac{\lambda d}{Y} \]  
\[ b_c = 1.22 \frac{\lambda d}{Y_0} \]  
\[ b_m = \frac{\lambda d}{Y_1} \]  

where, the Equation (2) allows to measure the width \( a \) of the simple rectangular slit, the Equation (3) allows us to measure the width \( a \) of the circular slit and the Equation (4) allows to calculate the number of lines per mm of the diffraction grating, knowing system parameters such as the wavelength of the light \( \lambda \), the separation distance between the slit and the observation screen \( d \) and the distance from the center of the spot of the pattern to the first minimum of intensity \( Y \) or to the first maximum of intensity \( Y_1 \).

Once the didactic system has been developed and the experimental assembly of Figure 2 is carried out, the process of capturing the image of the diffraction patterns through the camera is initiated, which is mediated by a code developed in Matlab for the achievement of the image and that allows to determine the relationship pixel/mm from the center of maximum intensity point to the secondary maximum, in Figure 4, the result of the experiment can be seen in following images:

![Figure 4](image.png)

Figure 4. (a) Digital capture of the diffraction pattern along a single rectangular slit, distance measured in pixels (b) digital capture diffraction phenomenon in a diffraction network of 600 lines/mm, distance measured in pixels.

5. Conclusions

In this research, a modular mechanical system was designed and manufactured in the form of modular optical bank piece by piece using a 3D printer, which constitutes a novel way to design and manufacture low-cost didactic elements that allow the development of modular structures for teaching in different areas of science. The printing of the parts of the optical bank and its modular construction, allowed us to improve many of the discomforts during the measurement process, such as to fix and adjust all the optical devices and measurement instruments with great precision, characteristics that are important in the processes of measurement in optical experiments which was complemented with a mobile application whose proper use facilitates the apprehension of the phenomenon of diffraction by students at different levels of education.
Otherwise, the design of the mobile application to be used in phones with Android operating system, allows students to check the experimental results, this element is an additional tool that allows students to compare their experimental results with the theoretical arguments.

Also, this research has allowed to verify the diffraction phenomenon using different types of apertures with low cost elements without reducing precision and accuracy in the experiments. In future work injection molds could be developed for the design of teaching tools: these can be accompanied by the use of elements such as CD/DVD discs, diffraction gratings, light sources, polarizers, diaphragms, among others, to improve the accessibility of the didactic resource to different types of users in different levels of education and thus reduce costs in the development of this type in the stage of experimentation. This project also applies to future designs and prototypes of own developments of the authors of spectrometers based on 3D printing and the manufacture of waveguide systems for the development of optical sensors.

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