Use of computer generated hyper-realistic images on optics teaching: the case study of an optical system formed by two opposed parabolic mirrors

Uso de imágenes generadas por ordenador en la enseñanza de la óptica: el caso de estudio de un sistema óptico formado por dos espejos parabólicos enfrentados

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Abstract

While the educational value of computer simulations is broadly accepted, it is also true that the student using them often encounters learning difficulties in not being able to fully identify what is seen to happen in the simulated model with what can be observed in reality. This is mainly caused by the highly schematic graphical interface of the simulation. A new method is proposed here which endows simulations with greater realism, making the identification of the model with reality far easier. On our case study, we generated and tested with our students several hyper-realistic images and animations of an optical system consisting of two parabolic mirrors. In light of the results and given the burgeoning growth of distance teaching, we believe that this new type of computer-generated images is destined to play a major role in the virtual laboratories of optics practicals, complementing traditional simulations.

Keywords: *simulations, teaching/learning strategies, virtual reality, interactive learning environments.*

Resumen

Aunque el valor educativo de simulaciones informáticas es ampliamente aceptado, también es cierto que el alumno que las utiliza encuentra con frecuencia dificultades de aprendizaje al no ser capaz de identificar plenamente lo que ve ocurrir en el modelo de simulación con lo que se puede observar en la realidad. Esto es causado principalmente por una interfaz gráfica muy esquemática en la simulación. En este trabajo proponemos un nuevo método que dota a las simulaciones de mayor realismo, por lo que la identificación del modelo con la realidad es mucho más fácil. En nuestro caso de estudio, hemos generado y probado con nuestros alumnos varias imágenes y animaciones hiperrealistas de un sistema óptico formado por dos espejos parabólicos. A la luz de los resultados y dado el auge de la enseñanza no presencial, creemos que este nuevo tipo de imágenes generadas por ordenador están destinadas a desempeñar un importante papel en los laboratorios virtuales de prácticas de óptica, como complemento de las simulaciones tradicionales.

Palabras clave: *simulaciones, estrategias de enseñanza/aprendizaje, realidad virtual, entornos interactivos de aprendizaje.*

INTRODUCTION

Practical laboratory experience is considered essential to ensuring that science students receive adequate training (Hofstein, Lunetta, 1982). The interaction that takes place in the laboratory enables students to develop multiple skills, and facilitates the teacher's task of introducing problems of great educational interest. Nevertheless, one often faces many obstacles in terms of space, time, or economics against implementing laboratory practicals. These difficulties can be alleviated with the use of computer simulations of the phenomena under study (Chang, Chena, Lina, Sung, 2008; Finkelstein, Adams, Keller, Kohl, Perkins, Podolefsky, et al., 2005; Steinberg, 2000; Tolentino, Birchfield, Megowan-Romanowicz, Johnson-Glenberg, Kelliher, Martinez, 2009).

In most computer models of optical systems, the perception that the student has of the physical phenomenon is usually limited by the lack of realism. Consider as an example the case of an optical system consisting of two parabolic mirrors facing each other. The usual ray tracing computer simulations, based on the geometrical optics approach, fall short in showing the full extent of the optical phenomenon they are intended to simulate. However, thanks to the constant and rapid development of multimedia software and graphics programming, one can today create an invaluable teaching tool that endows computer simulations with an extraordinary realism that brings the model far closer to reality perceptually. The constructivist educational environment thus created, based on new technologies, enables students to achieve meaningful learning (Jonassen, 1999; Reigeluth, 1999).

The aim of this work is to validate the use of hyper-realistic computer-generated images on Physics teaching, which could complement traditional simulations. For this purpose, we use hyper-realistic computer-generated images (Martínez, Naranjo, Pérez, Suero, Pardo, 2011), in the sense that the images seem to come from a camera, and thus make it easier to identify the model with reality. On our case study, we shall generate hyper-realistic images and animations of two opposed parabolic mirrors.

MATERIALS AND METHODS

Techniques chosen: Ray Tracing and Photon Mapping

For our hyper-realistic simulations of optical systems, we needed a technique capable of faithfully and credibly representing them as well as being consistent with the underlying theoretical models. The technique that we believed best suited to our needs was the geometrical optics technique called Ray Tracing. This provides great realism in the synthesis of images since it models the path that light takes by following the rays as they interact with optical surfaces. The calculations are performed using a specific Monte Carlo algorithm for the synthesis of three-dimensional images which provides accurate simulations of such phenomena as reflection and refraction.

The basis of the functioning of the technique is to trace a path from the eye of an imaginary observer through each pixel of a virtual screen, accumulating the contribution of each of the scene's light sources at that pixel. However, since the vast majority of rays from a light source usually do not reach the observer, only a small minority of the rays from a source will be required to form our image. Therefor., it is unnecessary to waste time calculating and following those rays which will not contribute to the image. One very simple solution to the question of how to select the set of rays that will actually participate in the generation of a given scene is to see the problem in reverse. Instead of following the rays from a light source, one travels backwards starting from the observer's position. With this technique, known as Backward Ray Tracing (Arvos,1986), when there occurs an intersection between a ray and an object, one only needs to project new rays directly to each light source. The result is that the image rendering time in our simulations is reduced by several orders of magnitude. The original idea for the algorithm comes from an earlier technique called Ray Casting (Appel, 1968). This technique was subsequently enhanced by the inclusion of a new illumination model (Whitted, 1980), which added realism to the rendered image.

The main advantage of using this technique rather than others (such as systems of triangle meshes) lies in the realism of the images that are generated. For example, effects such as reflections or shadows which are difficult to simulate using other algorithms (those based on random sampling, for example) emerge naturally with the Ray Tracing algorithm.

For some of the simulations performed in this work, however, indirect lighting was needed. This is a phenomenon that the Ray Tracing algorithm was unable to simulate. For example, it cannot generate reflection or refraction caustics (one of the visible effects of indirect light). This is a serious limitation for cases such as the optical system to be presented in this work. To solve this problem, we had to implement a global illumination algorithm on top of the Ray Tracing procedure. The method we chose was Photon Mapping (Jensen, Christensen, 1998). This is capable of endowing the scene with a model of indirect lighting, thus allowing us to simulate more accurately the interaction of light with transparent media, allowing the emergence of realistic effects such as scattering and caustics.

POV-Ray

Having decided on the techniques that could realistically simulate optical systems, the next step was to select appropriate software with which to perform our hyper-realistic simulations. The program we chose was POV-Ray, Persistence Of Vision Raytracer (POV-Ray, 2008). This allows one to generate high quality three-dimensional images by Ray Tracing with the implementation of additional algorithms such as photon mapping. Furthermore, it is open source, zero cost, and available for almost all computer platforms.

POV-Ray allows representing objects internally by mathematical functions using a scene description language. This is a major advantage, since the user then only has to be concerned with the geometric description of the optical system. All the underlying optics (Snell's law, the Fresnel equations…) is already included as part of the program's source code (Dolling, Wegener, Linden, Hormann, 2006; Halimeh, Ergin, Mueller, Stenger, Wegener, 2009).

Another reason that led us to the choice of POV-Ray was that it is written in C++, so it can be exported to any system that has a compatible C++ compiler. This universality puts it ahead of other similar programs that are exclusive to proprietary systems. It is currently distributed pre-compiled for Macintosh, Windows, and Linux operating systems.

Check of the validity of POV-Ray for the simulation of optical systems

First, we needed to check the validity of the program we had selected. To this end, we used POV-Ray to simulate simple optical systems – opaque polished surfaces capable of reflecting light, i.e., simple first surface mirrors. The results faithfully reproduced the behavior of a light ray reflected in a section of both concave and convex spherical mirrors. Fig. 1 shows, by way of example, some of the images generated versus photographs of the real phenomenon.

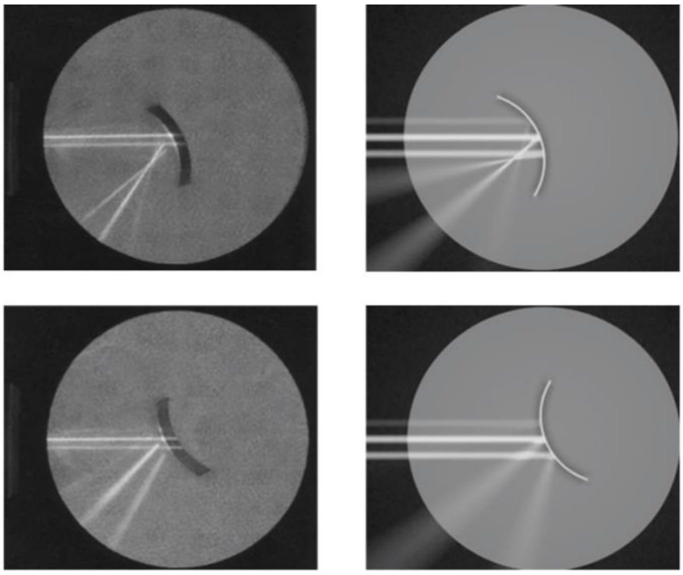


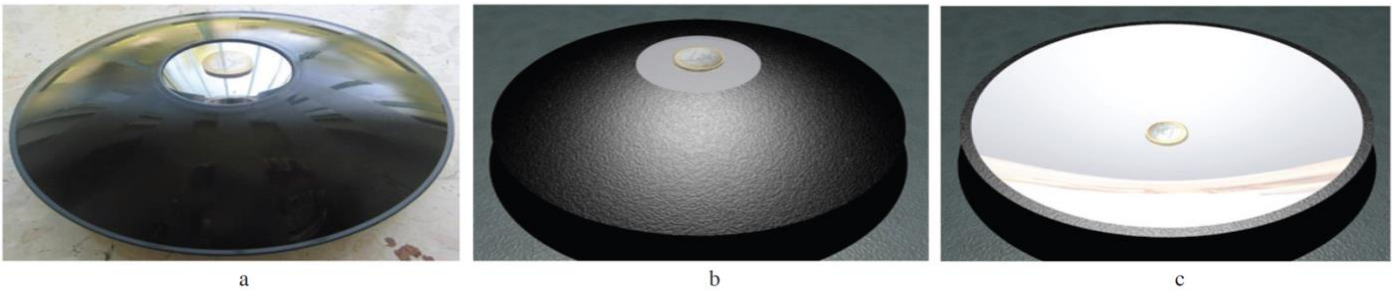
Fig. 1. Photographs (left) compared to hyper-realistic computer-generated images (right) of various beams of light reflected from a section of a spherical concave mirror (top) and from a section of a spherical convex mirror (bottom).

Hyper-realistic recreation of an optical system formed by two opposed parabolic mirrors

After having verified that the program POV-Ray was valid for our recreations of simple optical systems, and that the results of these trial systems were consistent with theory and gave a realistic appearance, we next carried out hyper-realistic generation of images of optical elements not usually found in basic optics laboratories.

In particular, the system we represented consisted of two parabolic mirrors, one face up and the other (with a hole in the center) placed face down on the first in the form of a lid. The center of the bottom of the first mirror coincided with the focus of the second. A small object was placed at this center point, hidden from view of an outside observer. With this configuration, a real image of the object below is formed in the aperture of the upper mirror. On Fig. 2 we show screenshots of this system.

Why is the image seen in that position? One commonly finds (both in textbooks and on the Internet) diagrams such as that depicted below on Fig. 3, which attempt to explain the formation of this image by tracing rays inside the optical system. In practice, however, these are insufficient to explain the formation of the image at the place where it appears (Pérez, Suero, Pardo, Gil, 2003).



a b c

Fig. 2. Double parabolic mirror. (a) Real photograph. (b) Screenshot of the hyper-realistic computer-generated image. (c) Screenshot of the hyper-realistic computer-generated image, without the top mirror. Notice the real coin at the center of the bottom mirror.

Fig. 3. Figure copied from the Internet (similar to many others) that attempts to explain the formation of this image.

The explanation that usually accompanies these diagrams is as follows: "Two rays are drawn from the object which are reflected in the mirrors. The reflected rays intersect at a point, and that is where the image of the object will be." Given this figure, a student might ask the following innocent question: "Why is the image formed where a ray from a point on the right of the object intersects another ray from a point on the left of the object? What does the intersection of these two rays at a point have to do with the fact that the observer gets the impression that the object is at that point?"

The explanatory diagram that we use for the paths of the rays in the real or simulated system is shown below in Fig. 4.

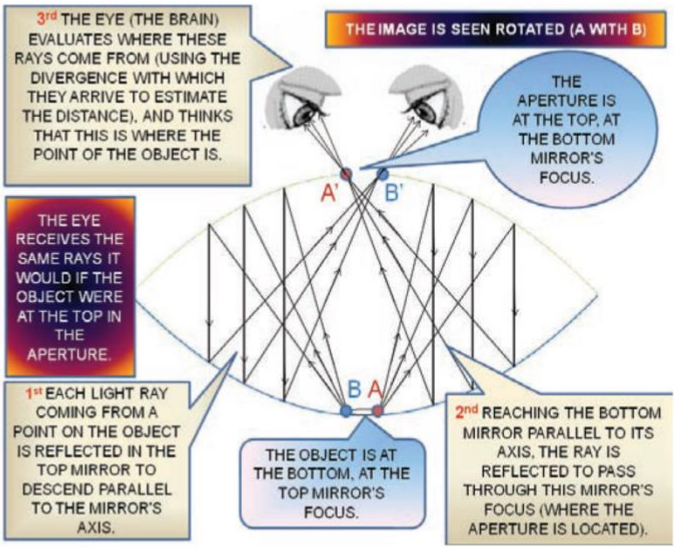


Fig. 4. Explanation of the diagram of the paths of the rays between two parabolic mirrors.

As is shown in the explanatory diagram, every ray of light leaving a point of the real object is reflected in the top mirror to descend vertically, parallel to the system's optical axis. (Since they are parabolic mirrors, every ray through the focus is reflected parallel to the optical axis, and vice versa). When the ray reaches the bottom mirror parallel to its optical axis, it is reflected to go through that mirror's focus, which is located at the aperture in the top mirror. All the rays from any given point on the object meet in a single image point.

The human eye, the brain, evaluates the rays reaching it. In particular, it evaluates the direction in which to look, and the distance as a function of the divergence with which the rays reach it. It then thinks that that is where the point on the object is (and from experience we will think that we can touch it if we put out our hand). Thus, the object is "seen" in the aperture because, as is shown in the explanatory figure, the eye is receiving exactly the same rays that it would if the object really was there. We have created an animation of this explanation in flash-video format, which we make available for our students on our Web site http://grupoorion.unex.es/optoelectronicaweb/index.html (click first on *'simulaciones'* and then scroll down to *'doble espejo parabólico'*).

Evaluation Instruments

To demonstrate the validity of these hyper-realistic simulations, we first compared the generated optical systems with their theoretical behavior, with the realism of their appearance, and with photographs of the real system. The experience was carried out during the 2009/2010 academic year with 25 Physics undergraduates of the Science Faculty in the University of Extremadura (Spain) who were taking an Optics course.

3. Analysis and discussion of results

The students who used these hyper-realistic images had no difficulty in identifying them with their real counterparts, and on several occasions some of the students said they were practically indistinguishable.

Given this concordance of the two opposed parabolic mirror simulation with reality, we believe that this new type of computer-generated images could improve traditional computer simulation. These new simulations, which we term hyper-realistic, may have an important role to play when the real device is not available in the laboratory. It would thus be an invaluable teaching tool for today's virtual (non-presential) learning platforms (Crippen, Earl, 2007; Jara, Candelas, Torres, Dormido, Esquembre, Reinoso, 2009; Martín-Blas, Serrano-Fernández, 2009; Rey-López, Díaz-Redondo, et al. 2008).

For the end-users to evaluate the proposal, two assessment instruments were used, designed respectively for teachers and for students:

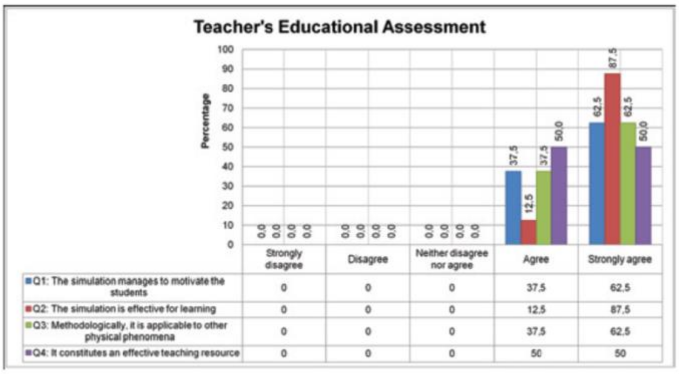
END-USER EVALUATION: TEACHERS' EVALUATION

For the teachers of the subject of optics, we prepared a questionnaire based on a 5-degree Likert scale (Likert, 1932). It consisted of evaluating four aspects related to the educational functionality of the simulation. In addition, there were four open items to allow feedback from the teachers in the form of comments and suggestions for improvement.

The goal of this first questionnaire was to ascertain whether the proposal:

- Manages to motivate the student.
- Is effective for learning.
- Is applicable to other physical phenomena.
- Is an effective teaching resource.

The chart on Fig. 5 shows the percentage responses of the teachers' evaluation of these four aspects.



	Strongly disagree	Disagree	Neither disagree nor agree	Agree	Strongly agree
■Q1: The simulation manages to motivate the students	0	0	0	37,5	62,5
■Q2: The simulation is effective for learning	0	0	0	12,5	87,5
■Q3: Methodologically, it is applicable to other physical phenomena	0	0	0	37,5	62,5
■Q4: It constitutes an effective teaching resource	0	0	0	50	50

Fig. 5. Percentage responses of the teachers' evaluation.

As one observes, the teachers gave an overall positive evaluation of the hyper-realistic simulation, since 100% of their responses to the four items were either "agree" or "strongly agree". Particularly noteworthy is that the highest scoring aspect was the effectiveness of the hyper-realistic computer-generated images for learning: 87.5% "strongly agreed" and 12.5% "agreed".

End-User Evaluation: Students' Evaluation

In parallel with the teachers' questionnaire, we prepared a twenty-five-item questionnaire directed at students. Of these items, twenty were closed, based on a 5-degree Likert scale. The remaining five were open, to give the student the possibility of including comments which we subsequently used to analyze the advantages and possible facets that needed improvement.

The objective pursued in this second questionnaire was the evaluation of three attributes of the computer-generated images:

- Technical aspects.
- Educational aspects.
- Degree of coherence between the real system and the hyper-realistic system.

In working towards this objective, we first designed twenty-five closed items to score on the Likert scale. After an initial test with a pilot group, we discarded five of these items following the criteria of the specific LXRTest computer program applied to these preliminary results.

Of the twenty closed items finally included, four corresponded to technical aspects of the simulation, ten to educational aspects, and six to the degree of coherence of the simulation. The items of these groups were distributed randomly through the test.

The data obtained from the questionnaire were subjected to statistical analysis using SPSS survey analysis software. The results are presented in the following chart (Fig. 6), which represents as percentages the distribution of the students' responses to each item, and the percentage distribution of their responses grouped into each of the three aspects – technical, educational, and coherence of the simulation with the real system.

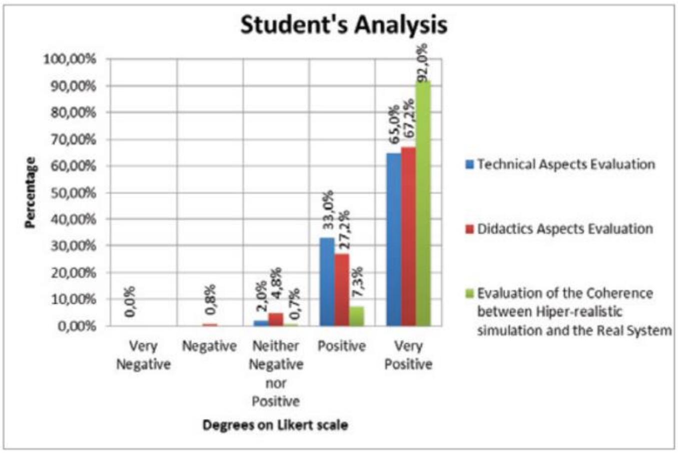


Fig. 6. Grouped distributions of the students' responses.

As was the case with the teachers, the students' general assessment of the hyper-realistic simulation was positive. They valued the technical and educational aspects of the simulation, and particularly strongly (92%) considered there to be a high degree of coherence between the hyper-realistic simulation and the real system.

CONCLUSIONS

The results of this work confirmed our initial assumption: that the use of hyper-realistic computer-generated images provides students with a better view of the physical phenomenon they are studying, and markedly reduces their difficulty in associating what they perceive in the simulations with the real phenomenon that can be observed in a laboratory.

The hyper-realistic images that we developed allowed the students to appropriately visualize the simulated optical system without the need for it to actually be available in the laboratory. Our proposal therefore constitutes on the one hand a supplementary educational tool to better understand the functioning of unavailable optical devices, and on the other a complement to real systems. Since they coherently reproduce reality, satisfying the theoretical model being represented to a far higher level of reality than that of traditional computer simulations, they are more likely to make assimilation of the physical concepts involved successful. This hyper-realistic quality is what gives our images a somewhat innovative quality, because they take into account not only the mathematical model describing the physics of the system, but also the realism of its appearance.

Given the present burgeoning interest in non-presential teaching, this new type of computer simulation is destined to become indispensable in the virtual optics laboratories of teaching at a distance.

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