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Web camera as a measuring tool in the undergraduate physics laboratory

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Abstract

An inexpensive Web camera connected to a personal computer with no additional hardware is used to measure position and light intensity. Three experiments: ink diffusion in water, pendulum damped oscillations and light diffraction are described. The measurements are done online and the results are observed on the computer screen in real time. The configuration is simple and cheap, suitable for demonstrations and laboratory exercises.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

The personal computer (PC) is used in the undergraduate physics laboratory to perform many different functions and can often replace expensive parts of equipment. Connected to appropriate sensors, it can control the experiment by measuring many physical quantities with good precision.

The standard PC hardware gives the possibility of interfacing a wide variety of experiments to computers quickly and easily. For instance, the computer sound card has been used as a primary data acquisition instrument [1] and the computer mouse has been adapted to serve as an inexpensive interface for motion and position measurements [2].

The Web camera is another widespread very cheap peripheral device. In this paper, we demonstrate how it can be used in undergraduate physics teaching laboratories for measuring the positions and the brightness of objects. A computer with a connected digital camera can collect data in real time and can be used for many different types of demonstrations and experiments on motion.

The use of a Web camera as a measuring tool is illustrated here by three examples: diffusion of ink drop in water, pendulum damped oscillations and light diffraction. The oscillations and diffraction are traditionally studied in the undergraduate physics laboratory, that is why we discuss them briefly; the measurements of the diffusion are explained in more detail.

2. Diffusion of ink drop in water

2.1. Theoretical description

Our first example is a remake of the investigation of ink diffusion in water published in [3]. A drop of ink is put into a Petri dish filled with shallow water. The growth of the ink spot can be described by a two-dimensional diffusion equation:

$$D\left(\frac{\partial^2 C}{\partial x^2}+\frac{\partial^2 C}{\partial y^2}\right)=\frac{\partial C}{\partial t}.$$

If we assume that in the initial moment the ink concentration $C(r,t)$ is distributed homogeneously inside a circle of radius a, the boundary conditions will be $C(r \leqslant a, t=0)=C_0$ and $C(r>a,t=0)=0$.

Expanding $C(r,t)$ as a Fourier integral and following [4], the solution of the equation can be obtained as

$$C(r,t)=\frac{C_0\,\mathrm{e}^{-\rho^2/4\eta}}{2\pi\eta}\int_0^1 \mathrm{e}^{-x^2/4\eta} I_0\left(\frac{\rho x}{\eta}\right) x\,\mathrm{d}x, \tag{1}$$

where $\eta = Dt/a^2$ and $\rho = r/a$ are dimensionless variables and I_0 is the modified Bessel function of zero order. The radius r of the ink spot in each moment t can be calculated as a size at which the concentration is

$$C(r,t)=0.001C_0. \tag{2}$$

2.2. Experimental investigation

The experimental setup to study the ink diffusion is very simple—the Web camera is placed above the Petri dish and is connected to a PC. A computer program written in Delphi object Pascal captures video frames from the camera each second. The photo visible on the computer screen has size 640×480 pixels in figure 1, a snapshot of the program screen is shown. The two scrollbars around the photo are used to scan it line by line (horizontal or vertical) and to choose a region for the image recognition (the blue rectangle in figure 1). The colour of each pixel is transformed to greyscale with a value in the range from 0 (white) to 255 (black). While the diffusion measurements are not started, the line greyscale profile is shown on the chart on the program screen. This profile is used to measure the background brightness and to set the value which defines the border of the ink spot. In our example it is 140, seen in the lower right corner in figure 1.

Black perpendicular axes with centimetre ticks are drawn on the white bottom of the dish. In the beginning, lengths of 1, 2 and 3 cm are measured over the two axes by clicking on the ticks, so the horizontal and vertical scales equal to the number of pixels per 1 cm are calculated. The measured ticks are marked by yellow circles in figure 1.

The image processing starts after ink is dropped in the water and in each second a new video frame is captured. The colour of each pixel which is inside the chosen region is transformed to a greyscale and if the value is greater than the chosen limit, a counter is increased. The surface S of the ink spot is calculated, dividing the counted number to the horizontal and vertical scales. The radius of the spot is calculated as $r^2 = S/\pi$ and drawn on the chart as a function of time. A red circle is drawn over the spot image with the same radius (figure 1).

In order to compare the measured dependence $r^2(t)$ with the one calculated according to (1) and (2), we need to know the diffusion coefficient D and the initial spot size a.

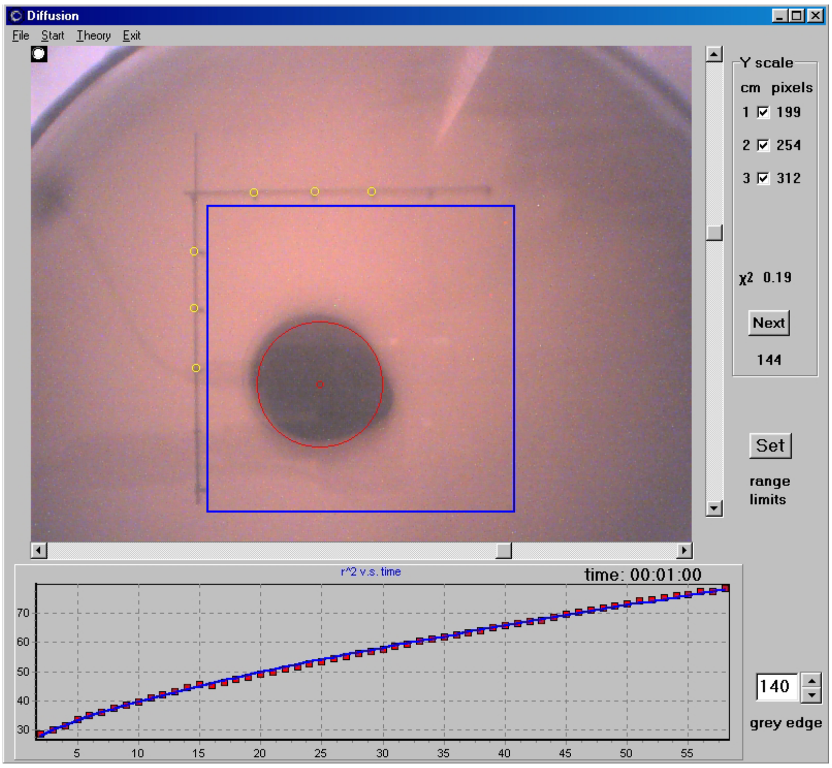

Figure 1. Snap shot from the screen of the computer program for investigating ink diffusion in water. See the text for details.

To find them, we used the Marquardt method [5] to fit the experimental data, treating D and a as free parameters. For this purpose, equation (2) is solved numerically and the obtained curve is drawn on the chart as a blue line in figure 1.

The result shown in figure 1 is obtained with Czech ink 'Centropen', and a good coincidence between the experiment and the theory is observed.

2.3. Computer software

Our program works under Windows operating system (98 or later versions). It uses Windows dynamical library avicap32.dll for video capturing and installed Web camera driver. The program is coded in Delphi, but any computer language could be used in the same manner. A working Delphi unit to open, grab and save video frames can be found and freely downloaded from the Internet [6].

All numerical methods needed for the theoretical calculation of the spot radius are included in the computer program. The transcendent equation (2) is solved using the bisection method, the integral in equation (1) is solved using the Simpson method, the nonlinear fit to the function $r^2(t)$ is done by the Marquardt method and the scales from pixels to centimetres are found using a linear fit. The Bessel functions are not included in the Delphi Math unit so we used additional procedure to compute I_0 in (1). All these or similar methods are studied by the students in the correspondent courses of computational physics or mathematics. All source codes can be found from the Internet.

3. Damped oscillations of a pendulum

The pendulum is widely used for educational purposes. The spread of the personal computers has stimulated the realization of experiments where the PC is used to measure the pendulum motion. Different methods to collect and process data have been proposed.

- The angle of pendulum rotation is measured by two spinning polaroids and data are transferred to computer via serial interface [7].
- A Kater pendulum is automated, using a capacitive sensor connected to a personal computer through an analogue to a digital converter [8].
- The position of a pendulum is measured by an ultrasonic range module, controlled through the parallel PC printer port [9].
- A sonic rangefinder (Automate Scientific Inc.) is used to log a detailed record of the position of an object as a function of time [10]. Experiments on oscillatory motion are described with three different damping effects.
- The angle of rotation is measured by a potentiometer fixed to the axis of the pendulum rod and a commercial PASCO Series 6500 computer interface [11].

Our pendulum consists of a bob, coloured in black, suspended on a string in front of a white screen. The Web camera is used in the same manner as is described in the previous section. The same procedures for image processing are used, but the video capturing is done each 100 ms now. Each photo is scanned pixel by pixel and the mean x, y coordinates for all pixels having a grey colour greater than the preset value are calculated. The time dependence of the x coordinate is drawn on a chart.

The motions of the pendulum are damped oscillations with an exponentially decreasing amplitude. Once the position as a function of the time is measured, the data can be analysed to obtain such fundamental physical parameters as period, amplitude, damping constant, velocity and acceleration. Different numerical algorithms can be used for this purpose. In our program, the amplitude is drawn on a second chart in each period and an exponential curve is fitted to the experimental data.

The computer program has the same output as the ink diffusion program (figure 1), but with a pendulum photo. It differs only in the part where the theoretical curve is calculated. We used the same Marquardt procedure to fit the amplitude which is measured as a maximum deviation from the middle position at each oscillation. The period is calculated as a mean value of the time intervals between two amplitude measurements. These calculations are additional to the previous program. The counting rate of 600 points per minute allows the use of more sophisticated numerical methods.

The descriptions of the harmonic and the damped oscillations are part of each textbook on general physics, that is why there is no need to do this here. Different problems related to oscillations and damping effects can be found in the cited literature [7–11] and studied using our method. The motion of pendulums with different constructions [8] can be digitized using a Web camera too.

4. Diffraction patterns

A series of classic experiments with a laser pointer as a light source, a ruler as an optical bench and a screen to measure the interference and diffraction patterns has been suggested [12]. In our third example, we use the Web camera to capture a video from a motionless object in order

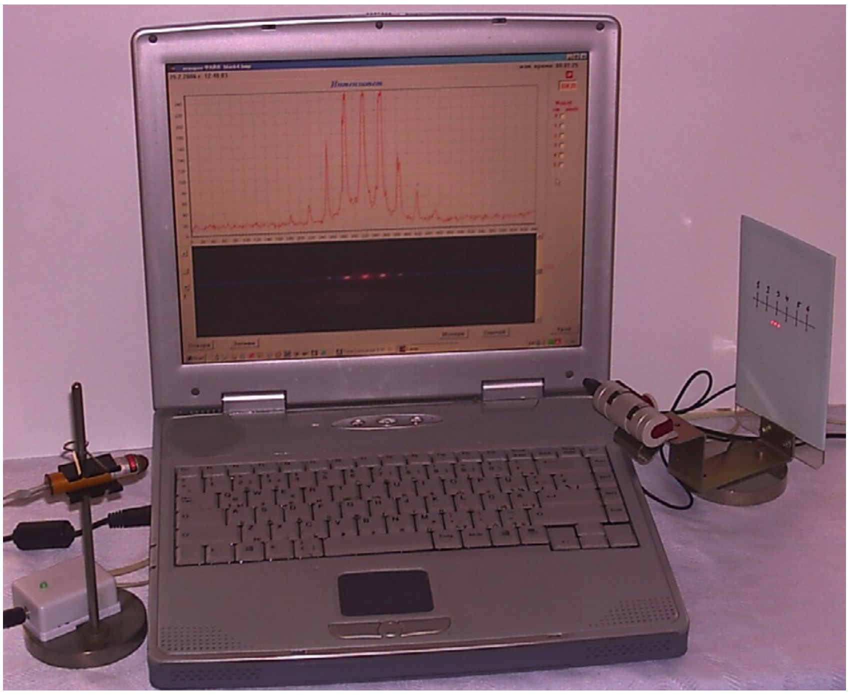

Figure 2. Experimental setup for observing diffraction patterns obtained by a laser pointer. The intensity of the diffractive picture seen on the screen is taken from a Web camera snap shot controlled by a computer program.

to measure not only the positions of the diffraction fringes, but their intensities too. A picture of the experimental setup is shown in figure 2.

A small piece of a diffractive grating is mounted into the cap of a laser pointer, which can be switched on/off by a computer program. The diffraction patterns are observed on a white or black screen. In this experiment, we use some hardware: the batteries of the laser pointer are pulled out and it is feed by an ac–dc adapter. In the small white box in figure 2, a trimmer is mounted to adjust the supply and transistor through which it can be switched. We use the computer printer port to interface this switch.

To obtain the intensity distribution of the diffraction patterns, we used another software for capturing pictures from a Web camera. In this case, we need to control the brightness and the contrast of the picture in order to avoid the camera saturation. A freeware library of routines that simplify the acquisition of images from TWAIN-compliant devices can be downloaded from [13].

The laser pointers are sold usually with many caps where different gratings can be mounted. In such a way, different patterns can be observed changing laser caps. Starting with a known grating constant, the light wavelength λ can be found. A typical intensity distribution is seen on the computer screen in figure 2 above the photo of the diffraction picture. It is obtained by scanning a line of this photo and transforming the colour of each pixel to a greyscale. The line can be moved up and down by a scrollbar, seen right from the photo. The measurement of the pixels to a centimetres scale is done in the same way as in the previous two examples.

After the scale is measured, our program gives a possibility of comparing the intensity distribution as a function of the distance from the central maximum x with the theoretical curve $I(x)$:

$$I(x) = I_0 \frac{\sin^2(\delta/2)}{(\delta/2)^2} \cdot \frac{\sin^2(N\gamma/2)}{\sin^2(\gamma/2)^2}, \tag{3}$$

where $\delta = 2\pi b \sin\theta/\lambda$, $\gamma = 2\pi d \sin\theta/\lambda$, $\tan\theta = x/l$.

The values of all parameters in (3): the distance between the laser pointer and the screen l, the grating constant d, width b and the number of rulings N can be adjusted. For this purpose, a second form can be opened (not shown in figure 2) and each parameter can be changed by a scrollbar. A good agreement between the experiment and the theory is achieved if the resolution of the Web camera is taken into account. For this purpose, function (3) is convoluted with a Gaussian function with a standard deviation of 1 pixel.

This experiment could be done manually in separate steps without any additional hardware and a special computer program: switch on the laser, take a snap shot of the diffraction picture and finally measure peak positions using any image editor program. Our setup has this advantage that everything is controlled by a computer. The intensity distribution is obtained and compared with the theory, and the influence of the different grating parameters can be demonstrated immediately. All this makes the setup very suitable for lecture demonstrations.

5. Summary and proposals

We have presented three experiments suitable for classroom demonstrations and laboratory exercises. In all cases, a Web camera connected to a PC is used to measure the position and light intensity of the observed objects. The configuration is simple and cheap; the computer software can be freely downloaded from the Internet. The authors share their source code too. The proposed method can be used for digitizing and data acquisition in many other cases.

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