Frame grabbing techniques in undergraduate physics education

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The availability of video and frame grabbing technology for desktop computers permits a new form of visualization and measurement in mechanics experiments. Simple systems such as bouncing balls can be studied in detail and with enough precision to determine important aspects of the motion. For example, the system can be used for introductory students to measure the acceleration of gravity, g, and it also can be coupled with advanced mathematical techniques to find the drag coefficient and elasticity of the bounce. Conventional spreadsheet programs can be used to carry out all but the most mathematical treatments of the data. Examples of analyses which were carried out by high school students through senior physics majors at college are given.

I. INTRODUCTION

Mechanics experiments and demonstrations in undergraduate physics often are carried out over a period of only a few seconds or less. As a consequence, stroboscopic pictures or elaborate encoding systems are used for quantitative studies of the motion. These methods require either large supply budgets, such as in the case of Polaroid pictures, or commercial interface systems. Modern video cameras of the ordinary domestic type, however, have the ability to take high shutter speed images at a very well known and precise rate and can therefore be used as a tool for the visualization[1] and quantitative analysis of physical phenomena. In the present article, we will describe how a video camera was coupled to a desktop computer, and how, with the aid of spreadsheets and other commercially available programs, it was used to study a bouncing ball. The results indicate that such a system can be used for a wide variety of mechanics phenomena, and that the approach is very useful in bringing the student up to a higher level of computer literacy, a goal generally recognized to be important in undergraduate physics education.[2–5]

The present study was carried out as a pilot project to study methods of improving introductory laboratories in undergraduate physics education. Summer students in NSF sponsored high school honors and research experience for undergraduates programs carried out a variety of projects with the equipment, which was provided by Michigan State University. The goal was to find a single, general purpose method for mechanics experiments and at the same time to develop a method which brought the students useful general abilities.

II. EXPERIMENT

A relatively high-quality video camera[6] was used to record events such as a ball bouncing, two air track cars colliding, or a collision on a billiard table. A fiducial back drop was placed behind these events. For example meter sticks were attached to the wall just behind the bouncing ball. A typical video lasted from 0.5 to 3.0 s. Shutter speeds of 1/1000 to 1/4000 were found to be satisfactory to freeze the action. The camcorder used was chosen to have high quality frame-by-frame playback without jitter. Lower price 8mm cameras were found to suffer from this defect, which would make the method useless. A better alternative would be to employ a high quality 8mm VTR, which are readily available with good frame-by-frame playback. A typical recording session with inexperienced students took about 10 min.

The video output from the camera was fed into the input jack of a video capture board[7] attached to one of the NUBUS slots in a Macintosh IIsi.[8] This board is capable of putting high-resolution color pictures onto the screen of the computer. The pictures were captured frame by frame by Media-Grabber[9] which produced standard PICT files. These files ranged in size from 50 to 626 Kbytes depending on the color or black and white resolution and the size of the picture. Recently available frame compression devices reduce the size and speed of capture to the point at which the computer could be used as a VTR directly. However this compression hardware was not available at the time that the hardware for these studies was purchased.

There are several possible ways to digitize the position of the object under study. A straightforward one was to use a commercial drawing program, MacDraw Pro,[10] which is capable of scaling the screen according to the apparent length of the fiducial and putting the cursor position out in real units. However, the cursor positions must be read from the screen and manually entered into a data book. The application has too many features and capabilities to be used for such a simple operation, and sometimes these features caused problems themselves for the students. For example, the AutoGrid feature of MacDraw Pro has to be disabled or it will cut the precision of the cursor placement significantly. A second way of encoding positions, which worked quite well, was via a HyperCard[10] program which

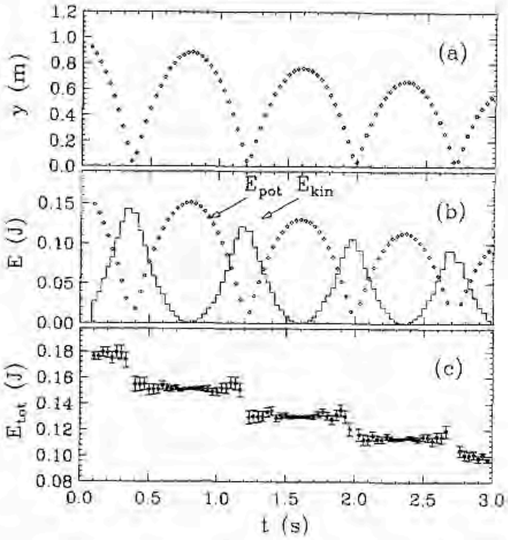

Fig. 1. (a) Time dependence of the position, (b) potential and kinetic energy, and (c) total mechanical energy of a bouncing ball.

was designed to read the PICT files and in a user friendly way guide the student through the digitizing and scaling process.[11] In this case, tables in text form were directly produced with information on the time and date and the name of the PICT files.

A very important aspect of the project was the use of spreadsheets to analyze the data from the text files. This is an effective way to deal with large amounts of columnar data, and it is now in use in many physics research projects. Students seem to learn spreadsheet techniques very quickly and apply them to other work they are doing. In this case we used Microsoft Excel,[12] which like MacDraw has many capabilities and features which are unused in the present work. Plotting with spreadsheets is satisfactory for looking at the data for checking purposes, but to produce the final graphs the students were taught to use the plotting package Kalleidagraph.[13] Kalleidagraph can also be used for curve fitting, for example to determine g from parabolic fits to y vs t for a trajectory problem.

III. RESULTS

Among the events, which were analyzed with the techniques described above, simple ball bouncing proved to be one of the most interesting. Balls of different types (squash, golf, ping pong) were dropped from a height of 1.0 m onto a solid table. The students were asked to find the traditional quantities which describe the trajectory including g, the acceleration of gravity.

Using a spreadsheet, the determination of velocity and acceleration from the position of an object in different frames is particularly easily accomplished by utilizing the finite difference two-point formula,

$$v_\Delta(t) \approx \frac{1}{2\Delta t}\,[y(t+\Delta t) - y(t-\Delta t)], \tag{1}$$

$$a_\Delta(t) \approx \frac{1}{2\Delta t}\,[v(t+\Delta t) - v(t-\Delta t)], \tag{2}$$

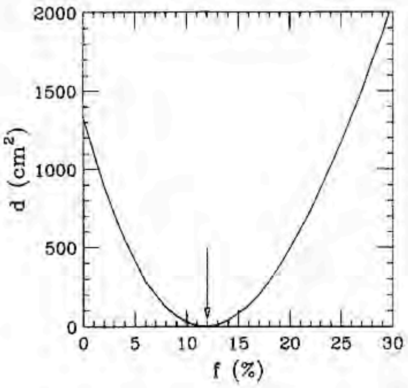

Fig. 2. Deviation, d, of the theoretically calculated trajectories from the experimental values as a function of the assumed energy loss fraction per bounce, f.

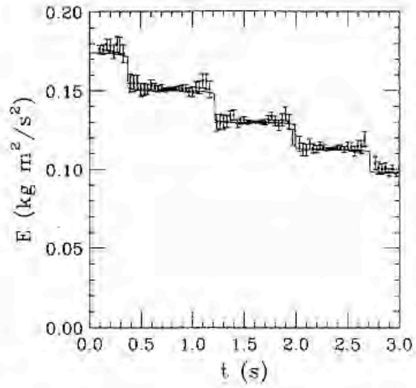

Fig. 3. Comparison of the experimental values of the total energy of a bouncing superball (plot symbols with systematic error bars) with the results of the calculations, where an energy loss fraction of 12% per bounce is assumed.

which are accurate up to error terms of $(\Delta t)^2 f'''(\xi)/6$, where f''' is the third derivative of y or v with respect to time, and ξ lies in the interval $[t-\Delta t, t+\Delta t]$. (In case of negligible air resistance, the trajectories of objects are parabolas ($y'''\equiv 0$), and these finite difference formulas are exact.) The value of Δt is of course given by the time difference between two subsequent video frames, $\Delta t = 1/30$ s.

As this point we should point out the danger of using the first-order approximation formula:

$$v_1(t) = \frac{1}{\Delta t}[y(t) - y(t-\Delta t)], \tag{3}$$

for which the error term is of first order in Δt: $y''(\xi)\Delta t/2$. Assuming again motion on a parabola, we have $y'' \equiv -g$ and so: $v_1(t) = v(t) + g\Delta t/2$. Computing the total mechanical energy, $E = E_{\rm kin} + E_{\rm pot}$, one, of course, obtains $E[v(t)] = \text{const}$. However, a computation of the total energy by using the approximation $v_1(t)$ instead of $v(t)$ yields:

$$E[v_1(t)] = E(t) + \frac{1}{8} g^2 m\Delta t^2 + \frac{1}{2} gm\Delta t - \frac{1}{2} mg^2(\Delta t)t$$

$$= \text{const.} - t\left(\frac{1}{2} mg^2\Delta t\right). \tag{4}$$

Thus for motion solely under the influence of a constant gravitational acceleration the use of a first-order numerical approximation to $v(t)$ yields the wrong result that the total energy, E, decreases linearly in time, whereas the second-order formula, Eq. (1), yields the correct result of a constant energy.

The students were also asked to find out whether the balls lost their energy in the bounce or rather in the frictional loss during the high velocity part of the motion. The quantity g was determined several different ways, including taking the average of the measured acceleration, fitting a linear curve to v vs t, and fitting a parabola to y vs t. The first of these was particularly interesting because it represented a real data analysis problem with a large data set, and it is a very interesting case for the propagation of errors.

Error analysis with a spreadsheet is very quick and easy to carry out. The coordinate space uncertainty in our measurements was limited by the number of pixels of the CCD camera, which in the ball-drop experiment was given by $\Delta y = 2.5\times 10^{-3}$ m. Since the velocities are determined from the positions, it follows from Eq. (1) that

$$\Delta v = \frac{1}{2\Delta t}\sqrt{2}\Delta y. \tag{5}$$

Since the total mechanical energy of the ball is given by

$$E = E_{\rm kin} + E_{\rm pot} = \frac{1}{2} mv^2 + mgy, \tag{6}$$

the uncertainty in the total energy of the ball is

$$\Delta E = \left(\frac{v^2}{2\Delta t^2} + g^2\right)^{1/2} m\Delta y. \tag{7}$$

In Fig. 1(a), we give the data for a superball (solid rubber ball) making three bounces. In Fig. 1(b), we show the derived quantities kinetic and potential energy. And in Fig. 1(c), the total mechanical energy (sum of $E_{\rm kin}$ and $E_{\rm pot}$) is shown including the systematic error bars calculated from Eq. (7). One can see that approximately 10%–15% of the total mechanical energy is lost in each bounce, whereas the energy loss in flight is negligible. This information is very difficult to determine in any other way.

It is interesting to observe that the error bars in Fig. 1(c) are largest where the kinetic energy is at maximum, and that they are smallest where the potential energy is at maximum. This is a simple consequence of Eq. (7) for the error propagation, which contains a velocity-dependent term.

Besides determining the introductory level physics parameters of the ball's flight, a more complex analysis can be carried out. For this analysis, we take into account that the ball also loses energy between bounces due to the influence of air resistance. The drag force due to air resistance is given by:[14]

$$F_d = C_d\,\rho_{\rm air}(\pi r^2)v^2, \tag{8}$$

where r is the radius of the ball, $\rho_{\rm air}$ is the density of air, and C_d is the drag coefficient. We solve the trajectory problem for the bouncing ball numerically by integrating the equations of motion including the effects of air resistance and gravity via a fourth-order Runge Kutta method.[15] For the bounces of the ball, we assume a constant energy-loss fraction in each bounce, independent of the height of the bounce. (Clearly this assumption becomes flawed, if one approaches large values of y, but for the present analysis this assumption proved sufficient.) The value of the drag coefficient C_d is dependent on the velocity of the ball. For small velocities, however, it is approximately constant and should have a value of $C_d \approx 0.5$.[14,16,17]

We determine the value of the fractional energy loss, $f = 1 - E_i/E_{i-1}$, in each bounce by measuring the maximum height in every bounce, $H_{i,\mathrm{exp}}$, $i = 1,2,\ldots,5$, and comparing these heights to the calculated ones by computing the difference

$$d = \sum_{i=1}^{5} [H_{i,\mathrm{exp}} - H_i(f)]^2. \tag{9}$$

The minimum value of d then indicates the best value of f (compare Fig. 2), $f = 12\%$. In Fig. 3, we compare the results of the calculations for the total energy of the ball as a function of time (solid line) to the experimental ones (plot symbols).

IV. CONCLUSIONS

Modern video frame grabbing techniques with a personal computer are becoming more and more accessible to the physics laboratory because the price of both has been dropping dramatically. A computer with a video card and an 8-mm video camera is a general purpose device for studies of mechanics at all levels of undergraduate education. The method is applicable to many cases besides trajectory motion, for example, collisions, compound and coupled pendulums, rotational motion, etc. An important side benefit of the scheme is that the students become familiar with standard computer techniques rather than the use of specialized lab equipment.

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