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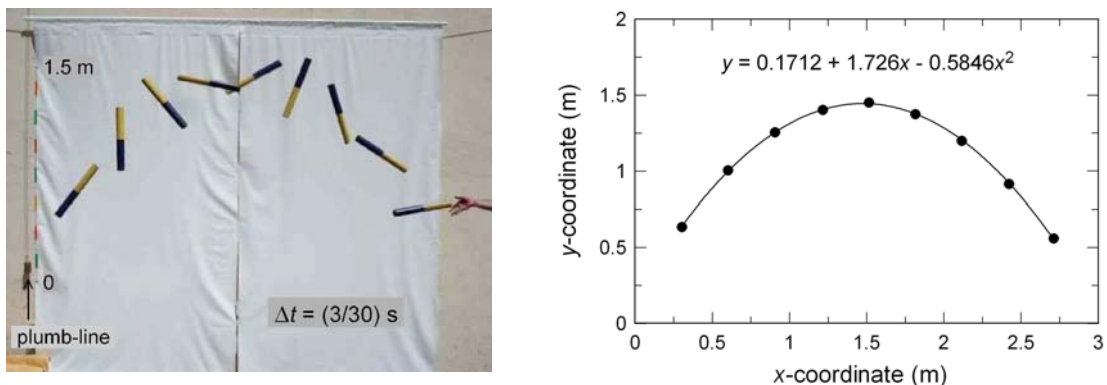
## Inexpensive Strobe-like Photographs

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The present work reports on a technique the authors have developed to produce and analyze, at very low cost, good quality strobe-like photographs like the one shown in Fig. 1. While the concept is similar to the one described by Graney and DiNotto<sup>1</sup>, the strategy here described benefits from recent advances in the fields of digital photography and related software to significantly reduce the costs, simplify the production process, and enhance the final quality of photographs of this type, as well as to obtain greater accuracy in measurements made with them.



**Fig 1.** **a)** Outdoor strobe-like photograph of the mid-air movements of a heavy, rotating metal pipe launched at an angle above the horizontal, obtained by blending nine frames of a video clip into a single composite image. To avoid excessive overlapping of the sequential images of the pipe, we only kept every third frame. Note the plumb-line and the 1.5-m metric tape on the left, to be used as references in the digitization of the pipe center-of-mass coordinates; **b)** the digitized  $x$ - and  $y$ -coordinates of the pipe's C.M. (solid circles), and the least-squares parabola (solid line).

Over the last and a half decade, some important articles on the use of digitized video for motion analysis have been published in this journal. David Wagner<sup>2</sup> was one of the first to “using a computer to track objects and measure their motion using a real-time base”, in this case the one provided by the time sequence of the frames in a video clip; in addition, he and his collaborators developed a system to

obtain the sequential  $x$ - and  $y$ -coordinates of an object moving on a plane by clicking the mouse directly on the object's image. Graney and DiNoto<sup>1</sup> introduced a convenient technique for combining several frames into a single "composite image that looks like, but is considerably less clear than, a strobe photograph". Laws and Pfister<sup>3</sup> have applied digital video analysis to a number of real-world events: collisions between football players, complex mid-air movements of divers after jumping from high boards, etc. Finally, it is also worth mentioning the article by Chow, Carlton, Ekkekakis, and Hay<sup>4</sup> who have developed a web-based digitized video system with application to the analysis of planar, projectile motion.

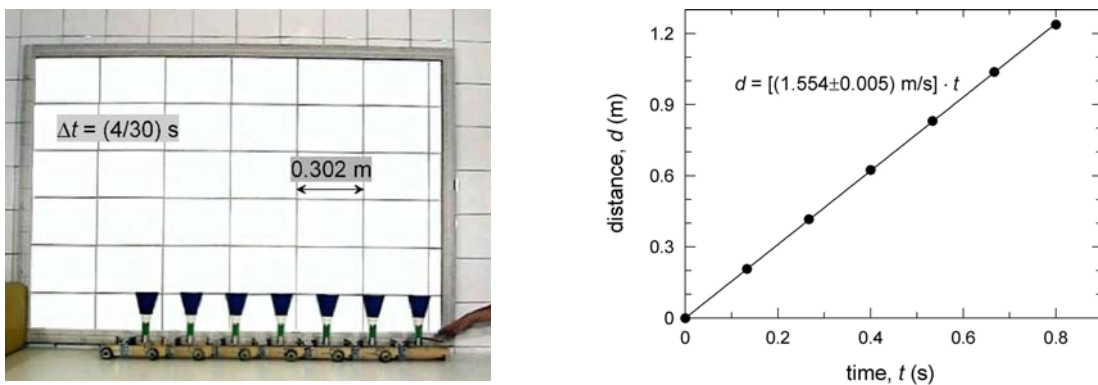
In conventional stroboscopic photography a single frame of the photographic film is repeatedly exposed whenever the flash of a stroboscopic light bulb illuminates a moving object; the frequency of the strobe lamp provides the real time step between successive positions of the moving object, and the inclusion in the photo of a metric ruler (or any other reference of known length) gives the real coordinates needed for the analysis of the motion of the object. In this type of photography the objects whose motion is to be analyzed are usually light-colored, and the background should be dark to avoid its overexposure by the repeated flashes of the strobe lamp.

In this article, we describe a different approach, opposite in some aspects to the one used in conventional stroboscopic photography. Here, the strobe-like photo is obtained from a video clip made of a *dark-colored* object moving against a *light-colored* background. The basic idea underlying this strategy can be summarized as follows: nowadays, most of the compact, low-cost, digital photo cameras allow, in addition, the user to make video clips with length limited only by the capacity of the storage media. In these low-end cameras, the user has no control on the exposure settings; the camera computer automatically calculates the "best combination" of exposure time ("speed", in the language of photographers) and diaphragm aperture (" $f$ -number") suited to the existing light conditions. Also, the  $f$ -values have a short range (2.8–5.6 for the Sony Cybershot DSC-W5 camera we have used), and the computer has, therefore, to adjust the "speed" in order to render well-exposed frames. If the moving object is a dark and relatively small one, and the background is as bright as possible, the camera light sensor will register the presence of a great amount of light, and will, therefore, force the use of high "speeds". This procedure will then lead to the very short exposure times needed to capture frozen, non-blurred images of the moving object. Such conditions have been achieved in developing this

technique by using basically an intense, artificial lighting inside a physics laboratory, as well as direct sunlight outside the school buildings.

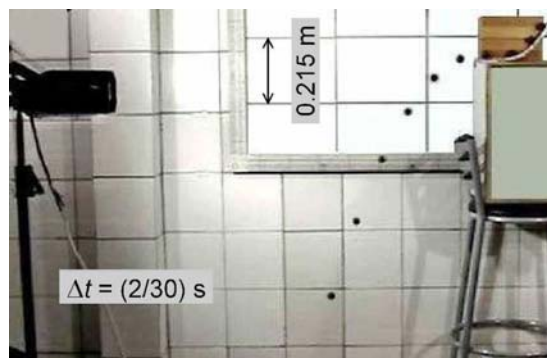
## 1. Apparatus and Procedure

In the first step, the short movies used to obtain the strobe-like photos were made with the camera mounted on a tripod. In the selected high-quality video mode, the camera shoots at a frame rate of 30 fps (frames per second). The indoor video clips used to obtain the photos in figures 2 and 3 have been filmed by illuminating a laboratory whiteboard with four 1000-W light bulbs. The whiteboard has been



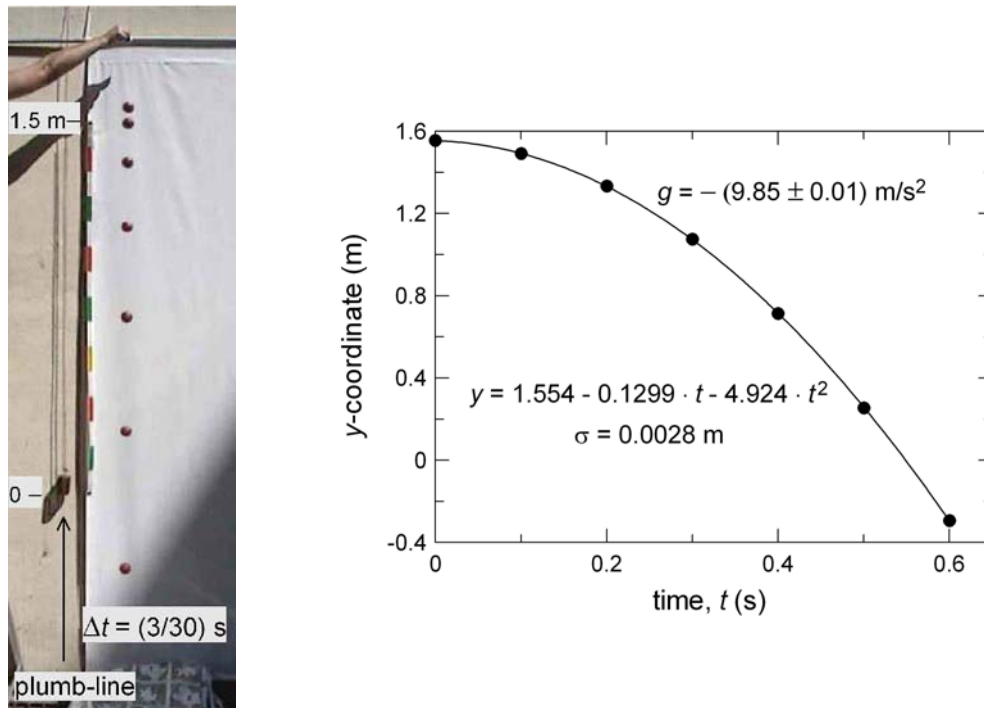
**Fig 2.** **a)** A laboratory cart moving at constant speed on a horizontal table top; for clarity, the frames have been edited to remove shadows of the cart projected on the background whiteboard, and to making this latter to appear more naturally;  
**b)** *distance* versus *time* graph for the lab cart in part a).

covered with A4-size (297 mm × 210 mm) paper sheets, separated from each other by 5 mm on all sides for a clear visualization of their borders when analyzing the photos; the distances between two successive borders are thus 302 mm and 215 mm for the vertical and horizontal borders, respectively.



**Fig 3.** Strobe photograph of the horizontal launching of a steel sphere; on the left, one of the powerful spot lamps used to intensely illuminate the background. A parabola fitted to the  $y$ -coordinates for the sphere positions led to  $g = (10.16 \pm 0.01) \text{ m/s}^2$ .

The outdoor video clips used to obtain the photos in figures 1, 4, and 5 have been made under direct sunlight in shiny days. For these pictures, the bright background was provided by homemade screens of white plastic or fabric, kept well stretched and in place by hanging them and using long, reasonably heavy metal pipes inserted through sleeves made throughout their bottom edges, and making sure that these edges were suspended in the air.

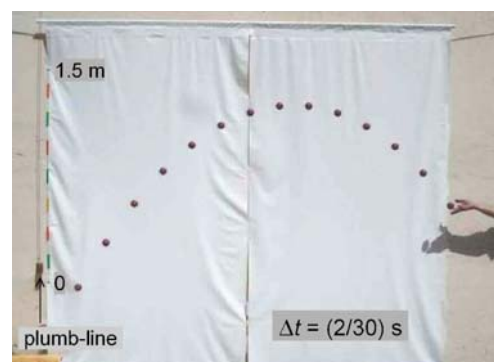


**Fig 4. a)** Outdoor strobe-like photograph of the vertical fall of a billiard ball. The seven frames have been edited to remove shadows. Also visible in the photo are the plumb-line, the 1.5-m metric tape, a blanket at the bottom to provide some cushion to the speeding-up ball, and the shadow cast by a nearby building (bottom right);

**b)**  $y$ - versus  $t$ -values (solid circles) and the least-squares parabola (solid line) leading to  $g = (9.85 \pm 0.01) \text{ m/s}^2$ .

To obtain high-quality photos one should avoid those daily hours at which the sun casts on the screen strong shadows of the moving object that might overlap with its image on the photo; the scenes should preferably be taken 2–3 hours before or after noon, when the shadows will be cast away from the object, making it easier their removal by editing the video later.

**Fig 5.** Outdoor strobe photo of a billiard-ball launched at an angle above the horizontal. (Note the 1.5-m metric tape on the left.)



The reference scale for the tracking of the coordinates of the moving objects was provided by a metric tape attached to the screen (note the tape on the left in Figs. 1, 4, and 5).

In the second step, the video file (downloaded to a computer) has to be open with any video-editing software that allows the user to extract individually selected frames as image files; in our case, the software used was the *AVS Video Converter*<sup>5</sup> (Online Media Technologies Ltd. (UK), ~US\$ 39), and the images were saved in JPG file format, with the same size (640×480 pixels) and resolution (96 dpi) of the original frames. With this software the user may also choose to quickly adjust the levels of contrast, brightness, sharpness, etc. of the video clip as a whole, a convenient feature that may enhance significantly the quality of the final strobe-like photos.

In the third step, all the extracted frames must be input into any software capable of combining the image files into a single composite photograph. This kind of “stroboscopic photograph” makes it a lot easier the tracking of the motion of the object by eliminating the need of marking its location at several equally spaced (in time) frames. For this purpose, the authors have used *Paint Shop Pro*<sup>6</sup>, from Jasc Software, Inc., later acquired by Corel Corporation and now commercialized as *Paint Shop Pro X2*. In working with this software, all the input image files appear in separate windows labeled initially as “background” layers; it is up to the user to choose which one must stay like that. The window containing the next image to be combined must now be made active, all its contents selected by choosing “Select All”, then copied (to the clipboard) and pasted onto the window with the background image by clicking on “Paste As New Layer”; the process is then repeated for each of the remaining sequential images. At this point, the window with the combined images shows only the last layer pasted (the one on the foreground), and its Layer Palette lists the blend mode currently chosen for each of the individual layers pasted onto the background. (The layer blend modes are methods of combining the pixels of the foreground layer with the pixels of the underlying layers.) The user may change from the default Normal blend mode to any of the several options available (Darken, Lighten, Multiply, etc.). While this choice may involve some trial and error until the best results are achieved, being also a matter of personal taste, the authors have found the Darken blend mode the most appropriate for the situations illustrated in

Figs. 1–5. In this blend mode, pixels in the selected layer that are darker than the underlying layers are applied to the image; pixels lighter than the underlying layers disappear. Since the strategy adopted in obtaining these composite strobe-like photos starts by shooting the video clip of a *dark-colored* object moving against a *light-colored* background, it is expected that the Darken blend mode should render the best results. However, different blend modes might be preferable depending on the application; we encourage the reader to try also other blend modes, for some of them provide very interesting results. All this process of combining the images into a single file is over only upon the saving of the file (in JPEG format, for instance); it is only then that the merged (or composite) image is generated; once saved and closed, this composite image can no longer be split into its separate layers when re-opened later. The layer blend modes described above do not introduce the kind of noise reported by Graney and DiNotto<sup>1</sup> when producing composite images with *Windows Paintbrush*.

## 2. Analysis of Strobe-like Photographs

The tracking of a moving object can now be done either on a computer, by using software that allows the digitization of the two-dimensional coordinates, or on a hard copy of the digital photo. This latter process, although cumbersome, has the advantage of dispensing the use of computers. Besides, this approach offers for kids at high-school level an opportunity to further develop their skills in carefully making measurements with a ruler, discovering the scale of a photograph, etc. One of the authors (E.L.M.) has been using this method with his 10th-grade students at Our Lady of Mercy (OLM) School (the American Catholic School in Rio de Janeiro) to analyze *i*) the horizontal component of the center-of-mass velocity of a heavy metal pipe rotating in the air (Fig. 1), *ii*) the speed of a laboratory cart rolling on the top of a table (Fig. 2), and *iii*) the horizontal component of the velocity of the ball in Fig. 3 (a steel sphere launched “almost horizontally”). By knowing the length (1.50 m) of the metric tape attached to the screen in Fig. 1, and the horizontal distance (0.302 m) between two successive vertical borders delimiting the A4-size paper sheets in Figs. 2 and 3, the students can calculate the positions of the moving objects at equally-spaced times; the time steps,  $\Delta t$ , have been conveniently chosen as 3/30 s in Fig. 1, 4/30 s in Fig. 2, and 2/30 s in Fig. 3. An example of such analyses is shown in Fig. 2b.

The analysis of non-uniform motions can also be carried out by careful inspection of printouts of the composite images. However, a more convenient (and faster) method consists in using appropriate software for the digitization of the coordinates of the moving object. An easy-to-use digitization method is the one built-in in Golden Software's *Grapher for Windows* (version 3)<sup>7</sup>. In brief, the first step consists in importing the JPEG strobe-like photo into Grapher and choosing the option *Assign coordinates* under the *Graph menu*; the user is then prompted to click on a point of the photo and assign to it real coordinates; having done so, he will be requested to repeat the process for a second point "with different  $x,y$  coordinates from the previous point"; finally, selecting *Digitize* from the *Graph menu* makes Grapher ready to associate real coordinates to any point at which the user places the cursor and click the mouse left button; as the points are digitized, a report is automatically generated in text format. The major advantage of this faster method is that, after having finished the digitization of all selected positions of the moving object, the user can open the saved report of  $(x,y)$  coordinates with the Grapher spreadsheet, then insert manually the values of  $t$ , and immediately analyze the results graphically by using the software tools. As an illustration, Figure 4b shows the motion of a billiard ball dropped from rest (photo in Fig. 4a); note that the parabola fitted to the digitized  $y$ -coordinates leads to  $g = (9.85 \pm 0.01) \text{ m/s}^2$ , a value only 0.6% away from the accepted one for the city of Rio de Janeiro ( $9.787899 \text{ m/s}^2$ ). This accuracy is comparable to the 0.1% relative error recently reported by Garg *et al.*<sup>8</sup> on their measurements of the acceleration due to gravity in Delhi (India); concerning precision, however, their method, which uses an "electronic drop tower" leads of course to a much more precise value, namely  $9.7998 \text{ m/s}^2$ .

We have used the digitization method above to also track the coordinates of the spheres in Figs. 3 and 5, as well as to capture the center-of-mass coordinates of the piece of metal pipe rotating in the air (Fig. 1). The main results of this work are as follows:

- a) The authors have carried out many runs of indoor and outdoor vertical-fall experiments with the steel sphere and the billiard ball; one of these runs is shown in Fig. 4. The corresponding  $y$  versus  $t$  graphs led to the expected parabolic behavior, with associated vertical accelerations in the range  $9.7\text{--}10.1 \text{ m/s}^2$ . The very small statistical uncertainties ( $0.01\text{--}0.02 \text{ m/s}^2$ ) and high accuracies (relative



errors less than 3%) that come out from these experiments clearly indicate that the technique of strobe-like photography described here is very appropriate for the analysis of motion from digitized video.

b) All the  $y$  versus  $t$  graphs for the cases in Figs. 1, 3, and 5 also led to the expected parabolic behavior, with associated vertical accelerations of  $10.60 \pm 0.02 \text{ m/s}^2$ ,  $10.16 \pm 0.01 \text{ m/s}^2$ , and  $10.30 \pm 0.01 \text{ m/s}^2$  for the metal pipe, the steel sphere, and the billiard ball, respectively. The latter two values are a little less accurate than the ones obtained from the analysis of vertical-fall experiments (previous paragraph). On the other hand, the  $g$ -value determined from the motion analysis for the metal pipe is clearly the less accurate among all the cases; we believe that one of the possible explanations for this discrepancy is the difficulty in locating accurately the metal pipe center-of-mass during the digitization process.

### 3. Final Remarks and Conclusion

The quality of the “strobe-like” photographs produced from video clips taken with compact digital cameras is limited by the standard size (640×480 pixels) and resolution (96 dpi) available in their video mode and is, of course, lower than that of the conventional stroboscopic photos, in which a single frame of tens of mega pixels is used. However, the precision and accuracy of measurements made on these composite photos are in general quite good even in the case the strobe-like photograph is made from raw frames that haven’t been edited to improve their visual quality. Significantly better qualities can be achieved after the treatment of the image by using any of the professional digital-photo editing software available at the market. In our case, some editing of the frames was done with *Paint Shop Pro*<sup>6</sup>, either to improve the brightness and contrast or to erase extraneous things appearing in the photos and strong shadows cast by the moving object. In doing so, we have been extremely careful not to alter any aspect of the moving object or the metric tape that might affect the measurements. Illumination is another key variable that affects significantly the final quality of the strobe-like photos; one of the advantages in using direct sunlight is that it provides a more uniform illumination of the background screen than artificial light.

On the limitations of the method concerning the speed of the moving object, we notice that even at its lowest position where the billiard ball in Fig. 4 is already moving at about 6 m/s, the ball's image still appears sharp in the photo. Hopefully, this technique could, under optimized conditions as for the background illumination and the object, be used for registering sharp images of objects moving as fast as 10 m/s, or even extend this upper limit to higher speeds in case a more sophisticated camera is used.

Finally, concerning costs, we had to buy the plastics for the homemade screens used as background in the outdoor sessions (about US\$ 10 for each 1.4 m  $\times$  3 m piece). Three metal pipes (amounting to ~US\$ 40) were needed: a long one (about 2.9 m) provided the support to hang the reasonably heavy screens (Figs. 1, 4, and 5), and two shorter ones (about 1.5 m each) were used at the lower ends of the screens to keep them well stretched and in a vertical plane. The old cart (Fig. 2) and the steel sphere are from the Phys Lab, and the other small items amount to less than US\$ 15. So, the only expensive items are *Paint Shop Pro* (~US\$ 80), and *Grapher for Windows* (~US\$ 349), general purpose software that might already be available at a school computer lab. At schools not equipped with these or similar software for groups of students, the teacher still has the alternative of using the method described in the present article by assigning fun homework projects to his students, asking them to creatively produce videos from their own ideas, even outside school grounds, and later hand in the video files to their teacher for the extraction and blending of frames into a single photo. Indeed, a student of one of the authors is currently planning to use the method for monitoring his progress in the PE classes of long- and high-jumping.

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