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The rolling with slipping experiment in the virtual physics laboratory—context-based teaching material

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Abstract

The Virtual Laboratory was created as a complementary educational activity, with the aim of working abstract concepts from an experimental point of view. In this work, the motion of a ring rolling and slipping in front of a grid printed panel was recorded. The frames separated from this video received a time code, and the resulting set of images can be visually inspected to determine the object angular and center-of-mass positions at known moments. From the positions versus time table, it is possible to analyse the dynamical evolution of the system and the ensuing physical interpretation of the ring rotation and translation. It is also shown here how this hands-on activity has been assigned to university students, that access the material from the website www.fep.if.usp.br/~fisfoto.

1. Introduction

In science education, it is important to contextualize the problem and/or the phenomenon before approaching the content related to its solution and/or explanation in the classroom [1]. As any resource used in teaching, an information and communication technology (ICT) tool needs a planned didactic sequence to build the student learning process. Bruner [2], exposed the idea of 'learning by doing', stating that the student has to interact with the object of study to gain experience and develop skills. Computer-based activities can, in many ways, contribute to achieve these objectives in physics education.

Tools based on ICT are being increasingly used in all scientific areas, as well as in the development of didactic activities [3, 4], among which are the Virtual Laboratories. In physics, simulations are often applied [5–8], but here we will discuss the use of videos of real arrangements. Recorded images of the motion of objects are frequently analyzed with the help of sensors or computer programs [9–15]. Delen [16] studied the effects of online video-based environments on learning activities making a broad analysis of the compiled works.

Our proposal relies on mechanics dealing just with position and time, and both variables can be cast in an image. Hence, from a video, it is possible to observe the motion of a body, analyse its kinematics and deduce the dynamics. This characteristic was extensively used in stroboscopic photos employed all along PSSC books on mechanics [17], where they provided starting points for the discussion of the underlying physics, avoided resorting to intuition and emphasized the role of experimental activities in science.

Theoretical classes that deal with rotational motion of rigid bodies have been brought forward by researchers [18–21], many of them using the methodology of explaining the topic with problem-solving activities. In this report, we show our virtual experiment on the rolling with slipping motion, give details on the specific physical content, describe and analyse the sequence of activities used to introduce the topic in our classes. A set of images separated from the video of a moving ring, that received a time code, allow the student to obtain primary data without using any software other than the web browser. The interpretation of the peculiar movement of the ring provides a good exercise on the simultaneous application of the equations of motion for translation and rotation, a central topic in rigid body dynamics. When studying this phenomenon, questions like 'Does the frictional force actuate until the end of the motion?', 'How can I know when the frictional force becomes null?' or 'When does the slipping motion stop?' deal with complex concepts that remain as doubts for most students when they do not have experimental activities to stimulate their inquiries.

The virtual laboratory, in the form of the experiment reported here, was undertaken in 2004, with a team of teachers and students. The free access web page www.fep.if.usp.br/~fisfoto stores the images and documents required to perform virtual experiments focusing on the translation and rotation of point particles and rigid bodies [22–24]. This material was prepared with the aim of contextualising lecture classes on mechanics with activities based on real physical phenomena. It does not intend to replace traditional laboratory activities, so important in any physics curriculum [25].

2. The virtual laboratory

In the preparation of a virtual experiment, the motion of a body, beside an instrument that allows the measurement of its position, is recorded. A digital time code is inserted in the video, with 10^{-3} s precision, to act as a chronometer, and a set of frames is isolated from the take. If the images are blurred, the odd and even lines in the frames are disentangled[3], which is sufficient to assure good pictures in many cases. After uploading the frames, laboratory guides, auxiliary documents, and images, the experiment is ready to be performed.

We record several runs in similar conditions for each experiment and allocate the corresponding selected frames as different sets to be analysed by the students, because the virtual laboratory is a graded activity. Owing to the use of *real* motion videos and the extraction of data by a person, statistical fluctuation warrants that the intermediate data and calculations will differ from group to group. The number of frame sequences that can be obtained from each film depends on the experiment, but in all cases we obtained many sets of frames to enforce work by each student group.

The student reads and registers in a spreadsheet, for each of the selected frames, the time code and the body position, using the rules or scales placed beside the object; this procedure avoids the use of specialized software to obtain the data, and requires that the learner actively searches the data by him/herself. After that, the body velocity along the motion is determined. Since the time interval between successive frames is very small, the average velocity is a very good approximation of the instantaneous velocity at the mean time. The analysis procedure depends on the experiment, but most of them allow different levels of detail, in particular, the uncertainty treatment may vary from absent to full data reduction, including parameter fit by the least-squares method. We prepared setups that reveal qualitatively the underlying physical law and, when analysed quantitatively, give results in

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[3] Many modern video recorders shoot the frames from upper left to lower right, scanning horizontal lines of the image progressively (*progressive scan*), but until a few years ago, almost all cameras, as that used in the experiment shown here, recorded interlaced images, in a time rate of 30 frames per second. They first shoot odd lines, then rescan the even lines of the same frame, always from upper left to lower right. This means that every spot in an interlaced frame contains images separated by about 1/60 of a second, which blurs the image of moving objects. The disentangled frames give clearer pictures of objects in motion than the complete frame.

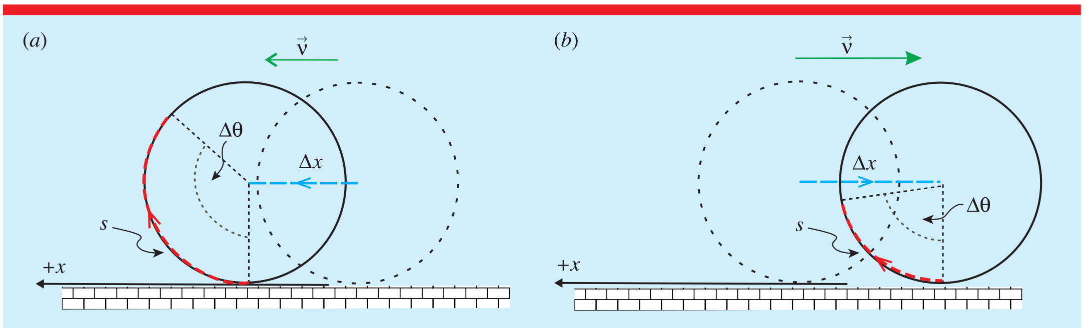

Figure 1. Schematic drawing of a ring rolling around an axis parallel to the floor and slipping on a horizontal surface while displacing to: (a) the left and (b) the right. The ring spins clockwise while displacing a distance Δx (in dashed blue line). The highlighted dashed red arc S represents the portion of the ring edge that contacts with the floor between the positions pictured in dashed and solid lines.

agreement with the physical model within experimental uncertainties.

The experiment guide, in the flap www.fep.if.usp.br/~fisfoto/rotacao/rolamento/index.html, introduces the experiment, raising questions whenever possible, and explains the procedure to obtain the successive linear and angular positions for the ring and describes the data reduction methods.

3. The rolling with slipping experiment

Any object with a circular cross section (sphere, cylinder, ring, etc) can roll on a horizontal surface with or without slipping. Phommarach *et al* [12] approached the topic of rolling *without* slipping using the recorded motion of cylinders rolling down a plane. With the help of the software *Tracker* they obtained the plot of the center of mass linear velocity with time and the trajectory of a point on the surface of the cylinder, illustrating the predictions of the theory. In our virtual laboratory experiment, we deal also with the rolling *with* slipping motion, aiming to shed light on the important physical concept that the equation of motion of the ring rotation around its center of mass (CM) is valid even if the CM is accelerated.

In the virtual laboratory, the time-stamped images from the snippet of the experimental arrangement allow obtaining translational and rotational velocities in function of time after measuring linear and angular positions of the ring. It is possible to identify the motion stages and perform a dynamical analysis, pointing when and where the translational and rotational accelerations are or not null and deduce whether or not the frictional force actuates.

3.1. Description of the motion

We restrict the analysis to the motion of a symmetric ring (the center of mass coincides with the geometrical center) rolling and slipping on a horizontal surface. Also, since the direction of the friction force depends on the kinematics, we derive the equations below when the ring rolls clockwise around its center as pictured in figure 1. There, the center of mass travelled a distance Δx and the ring turned an angle $\Delta\theta$. In the figure, it is also identified S, the arc length that contacted the floor while the ring described the angle $\Delta\theta$. The angular and linear center of mass velocities can be obtained with $\omega = \mathrm{d}\theta/\mathrm{d}t$ and $v = \mathrm{d}x/\mathrm{d}t$, respectively, where t is the time and θ and x are the angular and linear positions. When the ring slips, Δx and $\Delta\theta$ are unrelated quantities that must be dealt with different equations of motion. As θ and x are algebraic quantities, their signs must be taken in accordance with the adopted reference systems.

We adopted that clockwise rotations have positive angular velocity and the x axis points to the left. The relationship between angular and linear displacement *when the ring stops slipping* is

$$\Delta x = -R\,\Delta\theta \qquad (1)$$

where R stands for the ring radius. Note that Δx and $\Delta\theta$, as well as v and ω, have the same sign in the situation of figure 1(a) and different signs in figure 1(b). From equation (1), the condition of rolling without slipping is

$$v_n = -\omega_n R \tag{2}$$

where v_n and ω_n are respectively the translational and rotational velocities after slipping stops.

3.2. The adopted model

Regarding that the weight and the normal forces have the same line of action and their resultant is null[4], the horizontal component of the floor force on the ring is responsible for the variation of both linear and angular velocities. When $\sum \vec{F} = \vec{F}_f + \vec{N} + \vec{W}$, where the terms on the right side are the frictional, normal and weight forces, the equation of motion is

$$\sum \vec{F} = m\, \vec{a}_{\mathrm{CM}} \tag{3}$$

with $\vec{a}_{\mathrm{CM}}$ the acceleration of the centre of mass (CM), and m the ring mass. Here, the normal constraint floor force and the ring weight do not affect neither the rotational nor the translational motion of the ring. Therefore, $\vec{F}_f = m\, \vec{a}_{\mathrm{CM}}$, with $-|\vec{F}_f| = m\, a_{\mathrm{CM}}$, in accordance with the chosen reference systems. Thus, the center of mass linear acceleration, a_{CM}, is:

$$a_{\mathrm{CM}} = -\frac{|\vec{F}_f|}{m} \tag{4}$$

On the other hand, the frictional force produces a torque, $\vec{\tau}$, on the ring with respect to its CM:

$$\sum \vec{\tau} = \vec{r} \times \vec{F}_f = I\, \vec{\alpha} \tag{5}$$

where I and $\vec{\alpha}$ are the ring moment of inertia and the angular acceleration around the axis perpendicular to the ring plane through the CM, respectively, and $\vec{r}$ is the ring contact point position with respect to the CM. It is worth remembering that equation (5) is *not* valid in any other non-inertial reference system, and this exception is unique to the CM. From equation (5) and considering that $\vec{r}$ and $\vec{F}_f$ are orthogonal, the angular acceleration, α, projected over an axis perpendicular to the plane of rotation is

$$\alpha = -|\vec{F}_f|\, \frac{R}{I} \tag{6}$$

From equation (4), the CM velocity in function of the time is

$$v_{\mathrm{CM}}(t) = v_0 + a_{\mathrm{CM}}\, t = v_0 - \frac{|\vec{F}_f|}{m}\, t \tag{7}$$

where v_0 is the ring initial velocity. From equation (6), the rotational motion, with an initial angular velocity ω_0, is constantly modified in accordance with

$$\omega_{\mathrm{CM}}(t) = \omega_0 + \alpha\, t = \omega_0 - \frac{|\vec{F}_f| \cdot R}{I}\, t \tag{8}$$

Equations (7) and (8) are valid while there is friction. When friction ceases, both translation and rotation become uniform and the velocities follow equation (2). Therefore, substituting equations (7) and (8) in the condition of rolling without slipping, given by equation (2), it is possible to determine the instant t_{s}, the time when slipping stops:

$$v_0 - \frac{F_f}{m}\, t_{\mathrm{s}} = -\left(\omega_0 - \frac{F_f \cdot R}{I}\, t_{\mathrm{s}}\right) \cdot R \tag{9}$$

After t_{s}, the dissipative force disappears and both velocities become constants.

4. Materials and methods

The collection of pictures and documents needed to perform this experiment is located at www.fep.if.usp.br/~fisfoto/index.html, following the flaps ‘Experimentos de Rotação’, ‘Rolamento’, ‘Filmes e Quadros’.

4.1. Experimental arrangement

For the rolling with slipping motion experiment, we used:

- a 23’ diameter Aluminium wheel of a bicycle with two ribbons crossing at its center;
- a 2 m long printed panel with red and blue lines forming squares with 2- and 10- cm long sides, respectively;
- a digital camera (Panasonic 3ccd Minidv Pv-gs320).

The camcorder was placed on a tripod at ~2.5 m of the ring and ~0.4 m above the floor. Close-up

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[4] We are neglecting, as usual, the small differences that arise from Earth spin, the frictional force with the air, the buoyant force, little deformations of the ring and uneven floor.

and at-distance videos can be seen in 'EM CLOSE' or 'À DISTÂNCIA', respectively, in the experiment page, flap 'Filmes e Quadros'. As can be observed in the video snippet, the ring is thrown from right to left over a horizontal surface, rolling clockwise in front of a printed panel. Sometime the ring reverts its translation, while the angular velocity does not change its direction. This motion spans about 1.5 m.

We used the program Virtual Dub [26] to add the time code and disentangle the frames. Four independent films were obtained and three frame sequences were extracted from each one.

5. Student activities

After inspecting all frames from the take, the students measure positions and times to follow the motion of the ring and understand how the strips move along the quadrants of the reference system. The CM and the angular positions in function of time must be obtained, as described below.

5.1. Linear motion data

The origin of the reference system used to describe translation is chosen in an arbitrary position and kept fixed during data acquisition; figure 2 illustrates a convenient choice. The CM, where both strips intercept, and the time code are used to follow the ring position all along the experience.

5.2. Rotation data

We suggest to deduce the angle of the ring with respect to the x' axis from the angle formed by the strip that appears in the first quadrant with the x' axis, θ_a, as shown in figure 3 and given by:

$$\theta_a = \arctan \frac{y'_a}{x'_a} = \arctan \frac{\text{'number of vertical grid cells'}}{\text{'number of horizontal grid cells'}} \tag{10}$$

A guide-ray has to be chosen to measure the angular position of the ring, and θ is obtained by adding θ_a to a multiple of $\pi/2$ that corresponds to the quadrant where the guide-ray stays.

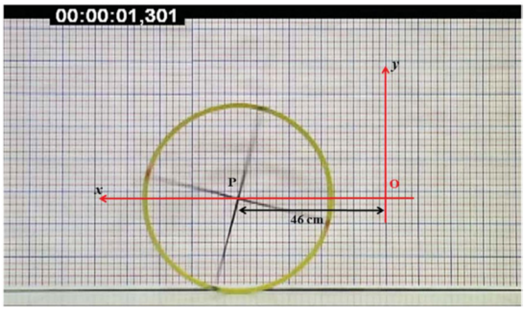

Figure 2. A frame of the video of the experimental arrangement, with the time code inserted at the top left corner. The adopted coordinate system was drawn over the image. The distance of the strips intersection, P, is measured with respect to the coordinates origin, O. Here, $x = 46$ cm when $t = 1.301$ s.

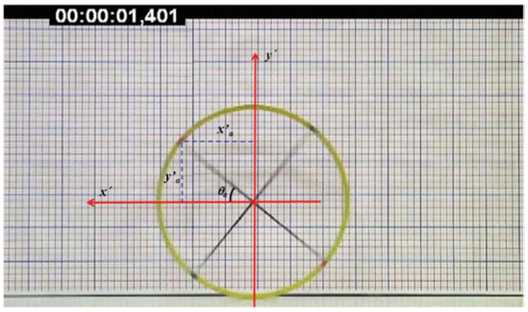

Figure 3. The moving coordinate system $x'\,y'$ used to follow the rotation was drawn over one of the extracted frames, to illustrate how the projections of the strip in the first quadrant, x'_a and y'_a, are used to obtain the angular position.

5.3. Analysis

Tables of position versus time allow to obtain the graphics on figure 4, that show how the ring linear and angular positions change with time. Translational and rotational mean velocities, $\overline{v}$ and $\overline{\omega}$, respectively, in the interval $[t_{(i-1)}, t_{(i+1)}]$, can be obtained with the measured linear, x_i, and angular, θ_i, positions and their respective times through:

$$\overline{v} = \frac{x_{(i+1)} - x_{(i-1)}}{t_{(i+1)} - t_{(i-1)}} \tag{11}$$

and

$$\overline{\omega} = \frac{\theta_{(i+1)} - \theta_{(i-1)}}{t_{(i+1)} - t_{(i-1)}} \tag{12}$$

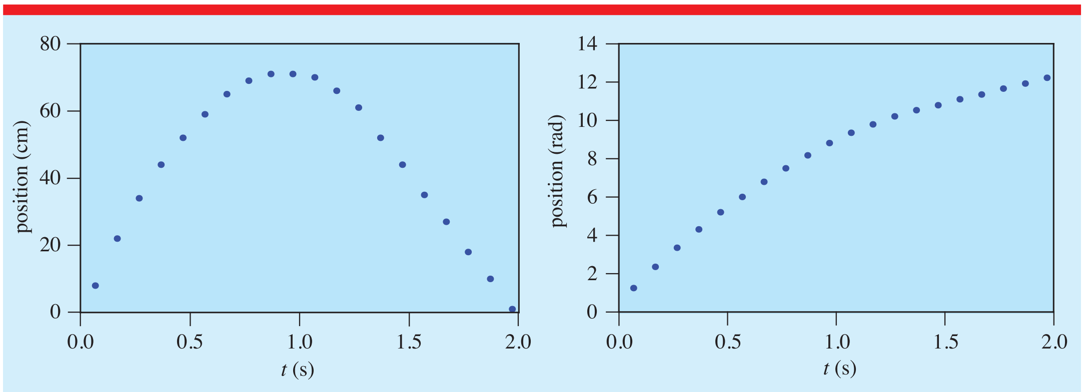

Figure 4. Ring centre-of-mass linear position (left) and angular position (right) in function of time. The data are represented by points, bigger than their respective uncertainty bars.

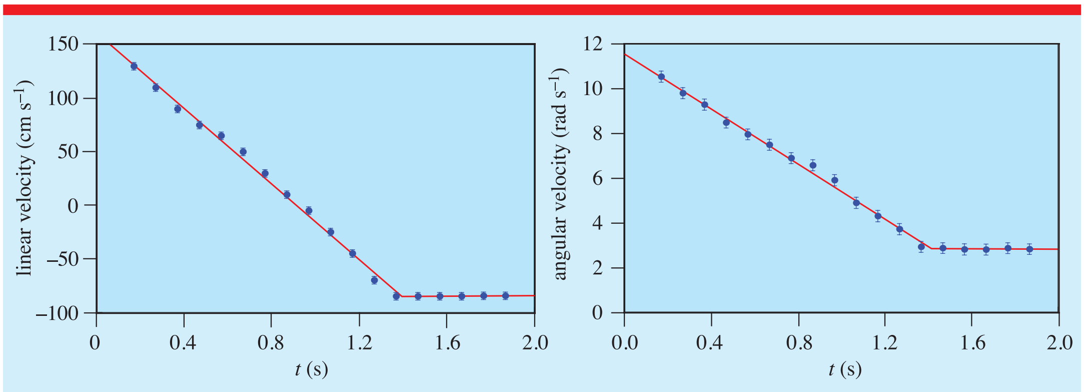

Figure 5. Ring translational and angular velocities in function of time. The experimental data are represented by points, with their respective uncertainty bars, and the tendency lines for both branches are drawn.

This linear and angular mean velocities are excellent approximations of the instantaneous velocities, because the time interval is very small. Hence we adopted $\bar{v}_{[t_{i-1},t_{i+1}]} \cong v(\bar{t})$ and $\bar{\omega}_{[t_{(i-1)},t_{(i+1)}]} \cong \omega(\bar{t})$, in the instant:

$$\bar{t} = \frac{t_{(i+1)} + t_{(i-1)}}{2}. \qquad (13)$$

The graphics on figure 5 show the experimental linear and angular velocities in function of time, calculated according to equations (11)–(13). It is seen that the center of mass linear velocity is positive at the beginning, goes to zero at ~1 s, changes sign, and becomes almost constant after ~1.4 s. The angular velocity does not change sign all along the motion, but decreases until ~1.4 s when it becomes nearly constant. The uncertainty bars shown in the graphics were calculated by the standard procedure.

The points on the different branches of the plots of figure 5 can be selected and tendency lines fitted. From the intersection of the two branches in the graphics, the student deduces the time when slipping stops. The results can be seen on table 1, along with those obtained from all parameters of $x(t)$ and $\theta(t)$ fitted by the least-squares method, when the uncertainties can be evaluated. This last calculation is an optional advanced activity—almost all our virtual experiments allow analysis in different depths, from simple graphics drawing to full data reduction that demands computational work.

6. Class practice

Figure 6 summarizes the rolling motion teaching activity sequence as we have implemented. The teacher asks the students to perform the virtual experiment and prepare a report, assigning a different set of frames for each group. They can access the site and, with the help of the experiment guide, deal with the phenomenon under study on their own. We organize special sessions where the students count on teaching assistants (generally advanced students), when any aspect of the measurements or physical analysis they are carrying out is not clear. This is an extra class activity and some students do not need any support.

The laboratory guide helps the students to extract the data from the assigned set of frames. Almost all students have no problem comprehending what to do, although many of them do not realise how the positions and times, read from the images, will allow them to understand the phenomenon. After obtaining the raw data, the students start the process of deducing the linear and angular velocities and the corresponding graphs in the function of time. Although these calculations are explained in the guide, velocities are abstract quantities, and understanding their meaning requires reflection.

Students prepare a report and submit it to the teacher. It's correction is considered an instance of review when the teacher evaluates it, gives a feedback and also offers to the student an opportunity to correct possible mistakes in the data acquisition and analysis process.

When students go to the classroom, the teacher formalises the theory. The film and set of frames are inspected once more to remark how the instantaneous center of rotation moves from an upper position to the contact point on the floor. Linear and angular velocities graphs, similar to those obtained by the students, help to deduce when the frictional force acts. The instant when rolling without slipping motion begins can easily been distinguished. We have found that most students clarify their doubts at this point, hopefully because they reach maturity after reflecting on the subject. Relating the virtual activity and its findings with the resolution of problems as they are found in textbooks is the next step in the teaching process.

7. Discussion

The use of videos as teaching material began in the mid-40s, with the advent of television [16]. Since then, this tool has been enhanced and used with increasing effectiveness. Much more than producing support or instructional material, videos can be a tool to develop a new strategy for contextualizing theoretical classes. A recorded experiment and the subsequent analysis of the images extracted from the video are an innovative way to bring the technology into the realm of teaching [14, 27].

Table 1. Instant of time when slipping stops, t_s, in seconds, evaluated from the velocity graphs (graphical) and by parameter fitting with the least-squares method (LSM), using the ring linear (translation) and angular (rotation) positions.

	t_s (s)	
Motion type	Graph	LSM
Translation	1.40	1.44 + 0.02
Rotation	1.43	1.46 + 0.05

A free access web page www.fep.if.usp.br/~fisfoto was developed to complement theoretical lectures on introductory mechanics in the Bachelor of Education course of the Instituto de Física, Universidade de São Paulo, and this particular experiment has been applied for the last four years to the students of the third semester. With the help of a spreadsheet program, students can verify and comprehend theoretical laws that govern the motion in an experimental and present-day style. An experience can be analyzed with different degrees of complexity, from a qualitative to a quantitative approach that includes uncertainty analysis with the least squares method. When analysed with statistical and computational tools, in certain cases, like the rolling with slipping motion, it is possible to obtain a precision that surpass some of the traditional laboratories, because the virtual laboratory works with an object and a measuring instrument in a frozen image with an accurately known time stamp.

Undertaking the analysis of the experimental data does not require advanced knowledge of numerical calculus. The interpretation of the mean velocity as instantaneous velocity in the mean time of each interval can be rigorously justified by the mean value theorem, which is in the syllabus of any first course in calculus.

Once the students obtain velocity graphs, it is easy to find misplaced points. It is a routine in the virtual lab to return to the student's report with wrong measurements to be repeated, which is possible because the frames stay in the web page and there is no need to have the equipment to redo the experience.

A virtual experiment is more interesting when it is possible to find an enticing question. In the rolling experiment, one of the common queries used in problem-solving activities is the determination of the instant when the slipping stops, often confused with the time when the linear motion inverts. This time can be experimentally obtained from any of the velocity graphs, when the tendency line become constant or by means of the translational or rotational position versus time plots, when the curves turn out to be straight lines. The other interesting question is related to the eventual disappearance of the friction force, which most students resist to accept.

The advantage of applying the virtual lab to the students before the formal lecture is that they go first through the analysis of the motion in the experiment to grasp the system properties and characteristics. When the students build velocity graphs for a moving object by themselves, the task of introducing the theoretical aspects that govern its motion is facilitated. After the development of the theory, a second round of quantitative analysis allows the students to understand the relationship between dynamical and kinematic properties of the system.

From our point of view, the virtual experiment, as described here, features:

(a) The visualization of a real phenomenon, stressing that physics deals with nature and man-made gadgets.

(b) The application of mathematical constructs to a real system, like the graphics of position and velocity, that represent the system evolution along the time and allow to understand its motion. Numerical computation of physical quantities by the student from his/her own observations provides insight into abstract concepts that otherwise may persist intangible. We have found that students are surprised by the simplicity of the position and velocity graphs they obtain.

(c) The evaluation of the dynamical parameters of a real system, like was explained in section 5.3, which is difficult to achieve by other methods. This allows the student to plunge into the quantitative aspects of the theory when the teacher goes back to the illustration.

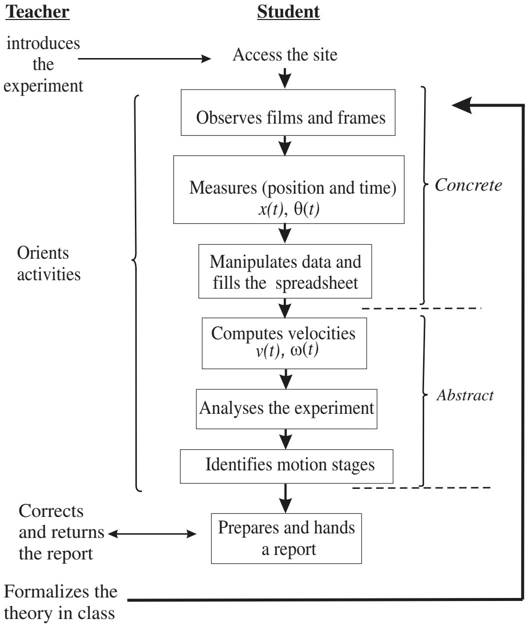

Figure 6. Sequence of the teacher and students activities as have been implemented.

(d) The determination of critical points of the system evolution. In this experiment, the instant of time when the slipping motion finishes is very clear in the graphic of velocity and convinces the students that it is *not* the same instant when the rings starts its way back to the pitcher.

(e) The observation of specific properties of the system. Physics resorts to build elaborate abstract constructions to facilitate and/or allow the understanding of complex phenomena. In the rolling motion, this is the case of the concept of instantaneous axis of rotation, that can be identified by the part of the strips that is not blurred by the ray rotation. Observing the set of frames in time sequence, it is possible to see a vertical displacement of the instantaneous axis of rotation from an upper position to the contact point between the ring and the horizontal surface, attained when the rolling without slipping condition is reached.

(f) The skill of taking measurements and other experimental competences, like the evaluation of the importance of concurrent physical phenomena. The virtual experiments deal with many different aspects of physics and ensue diverse analysis methods, that will help the student in future experiments.

(g) The strategy of beginning the study of a phenomenon from the experiment, in place of resorting to abstract activities like an schematic description of the motion.

8. Conclusion

A didactic tool that uses software and internet to access a virtual laboratory was described. It is known that context-based materials provided to students contribute to meaningful learning when they are potentially significant and involve them in the search for new knowledge within a cognitive structure to support this process [28, 29]. It was to fulfill these requirements that the virtual laboratory was created. It has shown an effective way to teach mechanics since students had already contacted with the experiment when the theoretical content was developed in the classroom. Lectures have shown more productive when students have questions that enrich the learning process.

Most of the qualities inherent to the virtual laboratory are shared with other activities, like problem solving, class demonstrations, the traditional laboratory, and formal lecture classes. The virtual lab interacts with these activities and helps to improve the understanding of the topic. As an example specific about the rolling experiment, once linear and angular velocities are plotted and the moment when they both become uniform is evaluated from the experimental data, it is natural to explain the dynamics of the motion. The disappearance of the friction force and consequently the torque on the ring, that happens when the condition expressed by equation (2) is reached, becomes apparent, and the theory can be explored deeply.

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