Virtual reality, video screen shots and sensor data for a large drop tower ride

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Abstract
Large drop towers let you experience a couple of seconds of nearly free fall before stopping gracefully in magnetic brakes or bouncing a number of times on compressed air, as in the Turbo Drop tower considered in this work, where many complementary representations are used. An accelerometer taken along on the ride captured the forces experienced by the body, and a pressure sensor provided a simultaneous proxy measurement of elevation. These data can be treated numerically: integration of the accelerometer data gives a velocity graph which can be compared to derivatives of the elevation data obtained from the pressure sensor. Plotting elevation versus velocity gives a phase portrait for the damped oscillations of the gondola before it comes to a stop. These abstract mathematical and graphical representations are complemented by screen shots from a video as well as from a virtual reality movie offering the view from the point of a rider. Forces and acceleration overlaid in a 2D version of the VR movie give a geometric illustration of Newton’s second law, in addition to the mathematical treatment. This work thus provides a wide range of representations, aimed to support student representational fluency and conceptual understanding of important force and motion concepts.

Keywords: amusement park physics, virtual reality, drop tower, acceleration, representations, first-person physics
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1. Introduction

Vertical drop towers are found in many amusement parks, offering riders spectacular views, while requiring only a small footprint in crowded parks. They are popular with parks due to their relatively low installation costs compared with traditional theme park attractions like roller coasters. Due to their often great heights their commanding structures positively enhance the skyline of theme parks. Drop rides also exist in underground forms, including the Haunted Mine Drop at Glenwood Caverns Adventure Park and Escape from Alcatraz in the United States, and the now-closed Nemesis: Sub-Terra at Alton Towers in the United Kingdom of Great Britain and Northern Ireland. Underground drop rides generally employ a substantially shorter drop than the above ground versions.

Rides involving vertical drops are also popular teacher assignments for secondary students, in particular rides involving a pure free-fall drop, where kinematic formulae can be applied. This is evident during science days, from queues as well as from discussions with teachers.

Developments in computers and software have enabled realistic simulations of experiences in amusement rides (e.g. by NoLimitsCoaster.com and vrcoaster.com), including virtual reality experiences [1]. The results were then compared to accelerometer data obtained on a smartphone [3–5]. The accelerometer data were integrated numerically to obtain the time dependence of velocity, which were then integrated again to obtain elevation. (Integration of numerical accelerometer data to obtain velocity and distance was also applied in earlier work for the horizontal launch of the launch coasters Kannen at Liseberg and Speedmonster at Tusenfryd [6] as well as during the slowing down in magnetic brakes [7].)

Data for the Gyldne Tårn were collected using the Wireless Dynamic Sensor System (WDSS) from Vernier (www.vernier.com), carried on the body in a special data vest, as shown in figure 3. Ten data points per second were collected, using the accelerometer and pressure sensors. An accelerometer, in spite of its name, does not measure acceleration but instead the vector \( \mathbf{a} - g \), often expressed as the dimensionless vector \( (\mathbf{a} - g)/g \), relating the force from the ride on a body to the force of gravity, with components depending on the orientation of the sensor, as discussed e.g. in [8].

For the purely vertical acceleration in the drop tower in figure 1 the acceleration can be obtained by adding the vector \( g \) to the accelerometer reading, or simply subtracting \( g = |g| \) from the vertical component. Figure 2 shows the data for acceleration together with velocity and elevation. The velocity graph was obtained by integration of the acceleration, whereas the elevation data are based on the output from the pressure sensor in the WDSS. The accelerometer data is somewhat noisy, as typical for amusement rides. Part of the noise can be attributed to ringing of the sensor following changing accelerations –jerk [9]. However, even noisy data can be useful for understanding the motion.

This paper explores a number of different visual representations of the motion of this drop tower, in addition to mathematical expressions and traditional graphs, thus providing teachers with additional tools to support students’ conceptual development and representational fluency. For example, Airey and Linder [10] note that ‘Visual representations are part of
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**Figure 1.** Sequence of screen shots of a Turbo Drop tower, the Gyldne Tårn (Golden Tower), at Tivoli Gardens in Copenhagen. The interval between the screenshots is 1.0 s and the distance between horizontal beams is approximately 2.4 m.

**Figure 2.** Elevation (blue) and accelerometer (green) data for the GyldneTårn ride at Tivoli gardens, collected using a WDSS sensor from Vernier. The velocity data (red) were obtained by numerical integration of the acceleration data.

**Figure 3.** Data collection using a WDSS sensor in a data vest. The little plastic mug contains a small amount of water, which will leave the mug as the gondola accelerates downward faster than the acceleration of gravity (Photo: Anna Hess).

After a discussion in section 3 about student recollections and difficulties in applying the laws of motion, the data shown in figure 2 are used to illustrate derivatives and integrals, to show how the mathematics and physics studied in the classroom can apply to more general situations than common textbook examples of uniform rectilinear motion, vertical free fall, projectiles and uniform circular motion. Section 4 shows an additional representation of the sensor data for the drop tower shown in figure 1: the velocity obtained by integration of the accelerometer data is plotted against the elevation giving
A few students may also mention jerk, \( \dot{j} \), as the time derivative of acceleration \([9]\).

The difference expressions in (1)–(3) were explored visually in the earlier work involving a sequence of screen shots of a small family drop tower \([2]\). A similar analysis can be applied to the sequence of screen shots in figure 1. During a lecture or recitation session, the screen shots could be shown, asking students where the velocity (or speed) is largest and where it is smallest. After establishing the relation between velocity and the difference in elevation been subsequent screen shots, the students can be asked to discuss where the acceleration is largest and if it is zero anywhere.

The corresponding integral forms of the relations are known to be less familiar (see e.g. \([2, 12–15]\)), but in a large student groups, a few students may come up with integral expressions, e.g. \( s = s_0 + \int v \, dt \) and \( v = v_0 + \int a \, dt \). For numerical data, these expressions are approximated by summation, e.g.

\[
\begin{align*}
 s - s_0 & \approx \sum_n v_n \Delta t_n \\
 v - v_0 & \approx \sum_n a_n \Delta t_n
\end{align*}
\]

Figure 4 illustrates the relation between derivatives and integrals based on numeric data displayed in figure 2. Class and tutorial sessions with many cohorts of introductory physics students have shown that many of them know derivatives and integrals from the formula sheet, but fail to connect with the definitions of derivatives and integrals as differences or sums with smaller and smaller time intervals. One of us recalls a discussion during a lecture, when a few students claimed never to have seen the summation sign in school. (They certainly had, but had obviously forgotten.) When asked how they did integrals these students happily exclaimed ‘we just use the expressions

\[
\begin{align*}
 a & = dv/dt \approx \Delta v/\Delta t \\
 a & = d^2 s/dt^2 \approx \Delta(\Delta s)/(\Delta t)^2.
\end{align*}
\]
on the formula sheet’, revealing a lack of connection to an important representation of integrals and how integrals can be useful. Numerical integration of authentic data, as illustrated in figure 4, provides a way to refresh their memory and bring meaning to the definitions. Working with these representations may lay a more solid foundation for their future studies, where these expressions for integrals and derivatives are often used to set up new relations.

Acceleration as second derivative of position may seem abstract, but when connected to force through Newton’s second law, \( \mathbf{a} = \frac{\mathbf{F}}{m} \), the experience of the body can be added to the more formal representations.

The acceleration graph in figure 2 shows that the ride accelerates downward faster than the acceleration of gravity. For downward accelerations larger than \( g \) the force from the ride must come from above, pressing the rider downward. This physical memory of a downward acceleration exceeding \( g \) may on special occasions be enhanced by bringing a little soft plastic glass with a small amount of water and see the water flying out at the top, as if the force of gravity were temporarily inverted.

Data collected from these free-fall rides offer opportunities to apply the more general relations (1)–(3) for velocity and acceleration, as well numeric integration, supporting student understanding of the concepts of derivatives and integrals, beyond analytical expressions found in their formula sheet.

4. Phase portraits of bounces

In the Space shot and Turbo Drop rides the fall of the gondola is stopped by compressed air, giving the riders a few extra bounces after the first drop, as seen in figure 1. Every bounce brings the gondola further down until it reaches the loading and unloading height. The phase portrait in figure 5 shows elevation versus velocity. If the bounces had been without energy losses, the phase portrait would simply have been an ellipse. The damping results in the size of the ellipse getting smaller and smaller. In addition, the lowering of the gondola is reflected in the centre of the ellipse being lower for every bounce.

Figure 5. Phase portrait for the bounces of ride in the Gyldne Tårn in figure 1, using the elevation and velocity data shown in figure 2.

Phase portraits are traditionally introduced in more advanced courses, but when students have collected their own data, this is an additional representation that may be explored without the full mathematical toolkit, as suggested also in [16].

5. Virtual reality in amusement parks

In an entertainment context, virtual reality (VR) is defined as a technology which ‘gives the guests a head-mounted display that allows them to see a digital world, matching the video image to the movement of the guest’s head’ [1, 17].

VR entertainment experiences in theme parks can be loosely grouped into several categories: VR added to existing physical rides such as rollercoasters, drop rides, waterslides; standalone ‘walkthrough’ experiences designed solely for VR where participants wear apparatuses that depict a different environment whilst they are physically walking through the ‘real world’; simulators where audiences are generally seated and the seats or vehicles they are on move in time with the VR experience; and entertainment ride or park-based experiences delivered via apps on smartphones and higher-end computer-connected headsets [1].
In theme parks, simulators enhanced with VR technology create exhilarating and immersive experiences: The body has limited precision in its discernment of steepness of slopes, and can easily be tricked into believing it is accelerating by tilting the seat, as used in simulators. Also, Newton’s first law tells us that a body cannot distinguish motion—only motion changes.

With VR Coasters (vrcoaster.com) headsets are placed on riders of active rollercoasters, where the VR visuals are coordinated with existing rollercoaster tracks with real forces, real drops and real airtime, to deliver an entirely new visual experience. VR devices can seamlessly trick users into believing they are in a different environment.

For example, a free-fall—or nearly free-fall—experience can be combined with VR to create completely different experiences, e.g. flying with dragons, as in the VR version of the Dæmonen roller coaster in Tivoli gardens in Copenhagen.

5.1. A virtual drop tower experience

Figure 6 shows an example of a few screen shots from the first bounce of a Turbo drop tower, taken from a 2D version of a VR movie simulating the ride experience from a first-person perspective. Turbo drop towers generally lift riders on a gondola to the top of the tower where they are held for a period of time and then either dropped or launched downwards, followed by a bounce on compressed air, moving partway up the tower before falling again for a number of iterations before being lowered back to the loading position. The VR representation offers an opportunity to view the ride from inside, giving a first-person perspective, in contrast to the more typical view from outside in physics textbooks (and in figure 1). The movie shows nearby objects seeming to move up while you move down and vice versa.

However, while velocity is relative, acceleration is absolute, it makes a difference if it is your body or the surroundings that is accelerating. Neither the outside view nor an inside VR representation can expose you to G forces different from unity if you are stationary, although if you have been on similar rides, you may recall the experience of the body.

To bring the relation between force and the changing velocity to students’ attention, the
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created the simulation of the ride and Paul McLaughlin and Nina Erdstein at SEEit who added the force overlays.

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Malcolm Burt produces video and virtual reality media experiences for amusement and education. He recently finished his PhD on what consumers want from a virtual reality entertainment experience.

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