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A rollercoaster viewed through motion tracker data

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Abstract

A motion tracker measures acceleration and rotation in three dimensions, sufficient for a complete determination of the motion. In this article, a rollercoaster ride is analysed with reference to motion tracker data. The use of this type of data in education is discussed as a way to deepen students' understanding of concepts related to force and acceleration.

Introduction

The train rolls slowly out from the station, down a very gentle slope, and turns right before it reaches the chain of the 40° lift-hill (figure 1). After the 'pre-drop' there is a right turn into the world's steepest slope in a wooden rollercoaster, leading into a $4g$ valley and then up again, into new turns, hills and valleys. The motion tracker Beowulf [1] misses nothing—except for the views and the traffic sign at the top, warning of the impending 70° slope.

A motion tracker sensor measures acceleration and rotation around three axes. In contrast to velocity, the acceleration and rotation are absolute. The measurements thus reflect the experience of the body. Data for 3D acceleration and rotation are sufficient to give a complete description of the motion. Through matrix operations, the results can be transformed between different coordinate systems.

Inertial navigation is only one of the applications that make use of measurements of the speed of rotation around a given axis without resorting to external measurements. A micromechanical gyro can, for example, be used for deployment of airbags, measurements of angular vibrations and real-time control of 3D images for computer graphics. Biomechanical measurements of a person's movements are useful, for example in sport training and in physical therapy. Beowulf weighs less than 100 g and includes three micromechanical 'butterfly gyros' with two small wings connected to an outer frame using three flexible beams. Using electrodes, the wings are made to vibrate so that the masses on opposite sides of the beams will vibrate towards each other. A rotation of the whole structure around the axis between the wings then results in a Coriolis force perpendicular to the gyro structure and to the motion of the masses. This results

Figure 1. The lift-hill and first drop of the Balder rollercoaster at Liseberg.

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in a torsional motion, which can be detected by a second set of electrodes, giving a signal proportional to the speed of rotation [1].

Acceleration and coordinate systems in amusement rides

In contrast to most textbook discussions of force and acceleration, the body accelerating in a rollercoaster may be your own, and the forces required for the acceleration are evident throughout the body. What the body can experience can also be measured with a co-moving sensor. Since the body moves in the gravitational field, $\boldsymbol{g}$, of the Earth, the additional force *per mass unit* required to obtain an acceleration, $\boldsymbol{a}$, is $\boldsymbol{a} - \boldsymbol{g}$. What is measured by an accelerometer is thus not acceleration but one or more components of this vector. Since the gravitational acceleration is used as a reference, it is natural to give results in terms of the ratio $(\boldsymbol{a}-\boldsymbol{g})/g$. This expression can be taken as a definition of 'g-force', which is a concept familiar to young learners but rarely mentioned in textbooks.

In amusement rides, it is obvious that the experience of the body depends on the orientation. A natural coordinate system to describe the experience follows the moving body, thus changing direction throughout the ride, and this is also the coordinate system used by the sensor to record the motion. Here, we define the positive z-axis to be the 'vertical' axis directed along the spine towards the head of the rider. The positive x-axis points to the front of the rider—in most rollercoaster rides, including this one, the x-axis concides with the direction of motion. The y-axis gives the direction of 'lateral' g-force. In a right-handed system it will point out to the left of the rider[1].

Figure 2 shows only the z-component of $(\boldsymbol{a} - \boldsymbol{g})/g$. Except for the time on the lift-hill, the x- and y-components would vanish for a perfectly banked rollercoaster if friction, as well as the length of the train, could be neglected. Figure 2 also shows angular velocities around the axes defined above. In the context of flight (and also, e.g., satellite navigation/attitude control), the rotations around these x-, y- and z-axes are referred to as 'roll', 'pitch' and 'yaw'. A webpage from NASA gives an illustration of the axes of rotation [2].

The Balder ride viewed through the data

Balder was voted the best wooden coaster in the world during its opening year 2003 [3]. It provides a very smooth ride, made possible through a new type of wooden track construction, where layers of prefabricated glue-laminated wood are milled to the precise rail form [4]. Balder also gives an unusual feeling of lightness. 'Negative gs' are experienced ten times, giving the impression of a lot of 'up' and not much 'down'. In many ways, Balder can be seen as a relatively simple 'special case' of a rollercoaster, as reflected in the motion tracker data discussed below.

We first consider the rotations around the z-axis, and note that the initial right turn shows up as an increasing negative angular velocity. This increase is a consequence of the downhill slope, causing the train to gain speed. Integrating the angular velocity over the time of the first turn shows that it is about 180° (i.e. π radians). This holds also for the following turns in Balder, showing, for example, that it involves no up- or downhill spirals, where the accumulated angle of rotation would be much larger. The long periods without rotation around the z-axis indicate that the motion of the Balder trains resembles a shuttle in a loom, up and down, out and back. All turns take place in relatively high positions, resulting in moderate g-forces during the turns, and contributing to the rider feeling light during the ride. The local height maximum leads to a speed minimum and to a corresponding minimum in angular velocity, which can be observed for many of the turns in the graph.

An initial positive rotation around the x-axis accompanies right turns, when curves are banked. Similarly, a corresponding negative rotation around the x-axis follows at the end of the turn when the banking ends, bringing the rider back to an upright position. The data for rotation around the x-axis show that Balder includes no screw—all rotations around the x-axis are significantly less than 90° before being followed by a counter-rotation.

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[1] This convention of direction of the coordinates is chosen because it emphasizes the forces from the ride acting on the body. The international standards are instead based on the force of gravity combined with inertial forces on the rider, making the positive z-axis point downward. In the US standard, the x-axis points forward, whereas for the European standard, it points backward (and the direction of the y-axis follows automatically for a right-handed coordinate system). Since inversion of all three coordinate axes would result in a left-handed system, one of the axes keeps its direction.

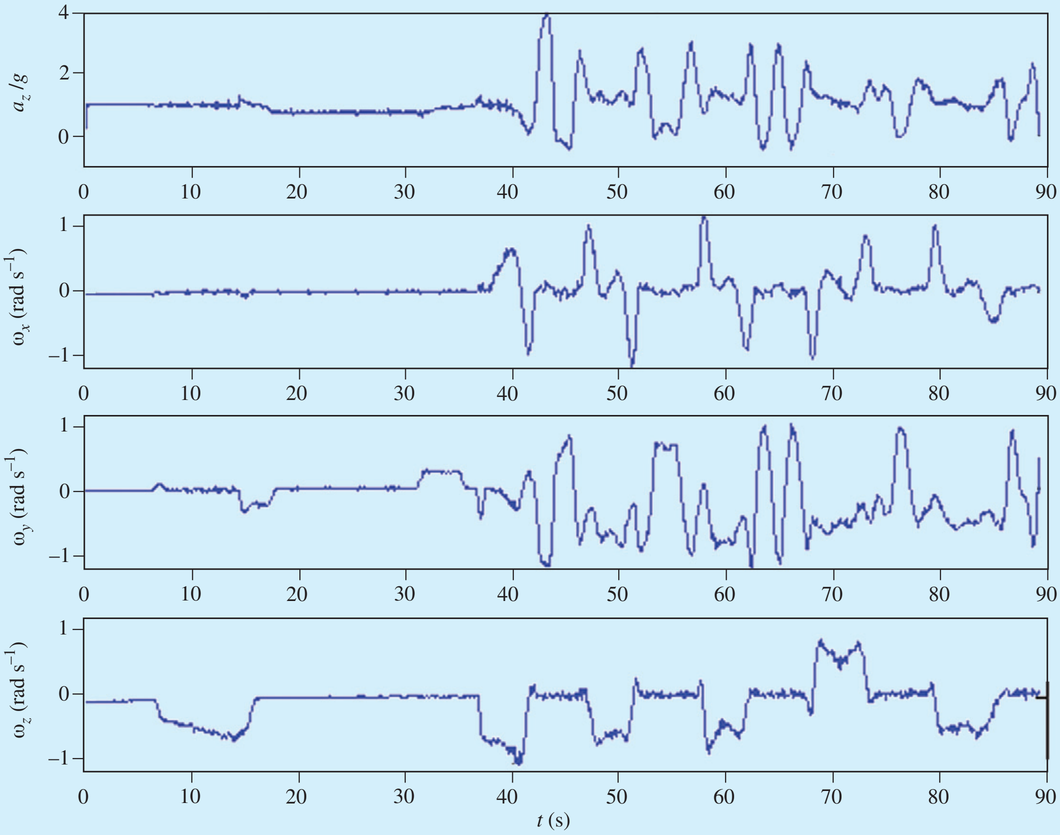

Figure 2. Acceleration and rotation data from Beowulf in Balder.

Many of the hills and valleys in Balder occur in sections of the track where the projection on the ground is a straight line and the only rotations are around the y-axis. With our coordinate conventions, a negative rotation marks a valley, e.g. following the first big drop. A positive rotation around the y-axis marks a hill. One example is shown in figure 3, where the track offers a built-in 'parabolic flight' and the rider experiences the longest period of near-weightlessness. As in the case of rotations around the x-axis, the lack of large rotations around the y-axis shows that Balder involves no loops.

A complication in dealing with rotations is that only infinitesimal rotations commute. Converting motion tracker data to complete specifications of the motion involves matrix manipulations that are beyond reach for students entering university. In addition, the numerical accuracy may be insufficient to bring the virtual rider back to the point of departure, i.e. to the station. Nevertheless, the data can be used in many ways for student investigations, as discussed below.

Calculations, measurement and authenticity

By combining accelerometer and rotation data, the expression for the centripetal acceleration, $a_c = r\omega^2$, can be used to determine the radius of curvature, r, in valleys and over hills. Combined with the rotation data, this also gives the speed.

The data shown in figure 2 were taken during a relatively cold morning in June, before the park opened. The train was notably slower than usual, especially toward the end of the track. A visitor who would like to know the actual number of 'g's during a visit can use the stopwatch on a mobile phone to measure the time required for the train to pass a given point. Combining this time measurement with a train length of about 15 m

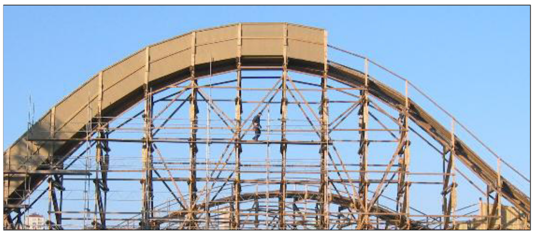

Figure 3. The section of Balder offering the longest airtime. The regular wooden structure provides 'Balder coordinates', where the distance between horizontal beams is 2.50 m and the distance between vertical beams is, in most cases, 2.75 m.

gives a value for the speed (although it is obvious that different parts of the train pass a hill or valley with somewhat different speeds). This value can then be compared to the speed estimate, $v = a_c/\omega$, obtained from the values for the angular velocity and centripetal acceleration at that point.

Recording data during rides is a common and rewarding 'science day' activity [5]. However, it also requires a considerable amount of equipment, managing and planning, as well as attention to safety. Even for a seasoned rider, a rollercoaster is not the optimal place to try unfamiliar measuring equipment. Using data recorded in earlier measurements can shift the focus from data collection to data analysis and physics discussions, as found by teachers who have tried alternative formats. The combination with ground-based time measurements makes it possible to obtain results that may vary between different trips on a ride, thereby making it easier to maintain a feeling of authenticity.

Using rollercoaster data in education

The motion tracker data set for Balder has been used during the last academic year in project work for different groups of pre-university and engineering students. The Balder ride was divided into four or five segments, assigned to different groups, whereas other groups worked on different types of data for one of the other coasters at Liseberg. Groups of 4–6 students were assigned one or two additional rides for closer analysis, with different rides for all groups. The work was presented in a written report followed by an oral presentation and discussion with 'opposition' from another group, who had had time to penetrate the report.

During the project work in the students' first two months at university, we have also discovered that students, at least in Sweden, leave upper secondary school with the habit of performing three measurements to work out an average of what needs to be measured. Still, they often have very vague ideas of measurement uncertainty, and often finish their report with an apology that the measurements may be insufficient for any conclusions at all. Based on this observation, we will insist next time that several group members perform individual measurements for the time of passage of several trains, to bring a discussion of uncertainty into focus.

As always with project work, different groups of student show various degrees of enthusiasm, persistence and ambition, but in most cases, using authentic data in an enjoyable setting inspires students to try to understand the data and connect them to the experience of the body. One student had built a wooden model of the Top Spin ride for the presentation. One group showed 3D animations of two rides.

Many students discussed the difference in ride experience due to the position in the train; the smooth ride in Balder makes it impossible not to notice the difference. A few of the students also performed calculations to work out the difference in g-force on the hills for different part of the train. Some students used the picture of the hill with the longest airtime (figure 3), converted the 'Balder coordinates' provided by the track to SI units and fitted a polynomial to the curve.

Rollercoasters and force concepts

One important aspect of using amusement rides in physics teaching is to gain a deeper understanding of the concepts of force and acceleration. In many ways, acceleration is more fundamental than force—the acceleration is shared by the riders in the train, whereas the force, of course, depends also on their mass. Still, in many reports, students insert a mass to work out the force. Many students tried numerical integrations of accelerometer data—and found themselves confused that accelerometers don't always measure just acceleration. This invites important discussions about what can and what cannot be measured from within a moving system, and the insight that even a 'black box' measurement is limited by the laws of physics.

When asked to draw a mindmap of acceleration, new students rarely refer to the experience of the body. Even if they are, in principle, aware of acceleration in circular motion, many of our beginning students fall back on an understanding of acceleration as 'increase of speed', possibly generalized to 'change in speed'. They would then tend to claim that the acceleration is zero on the top of a hill or in the bottom of a valley, where the speed has a minimum or maximum. We also find that many students may be able to work out the forces acting on the rider on a hill or in a valley, where all forces are along the same axis, but still have problems in more general two- or three-dimensional situations.

The quite unusual features of the Balder ride make it a 'special case' of rollercoaster, easier to analyse than the fully fledged space curves of many other rollercoasters. If the purpose of the project work is to help all students develop an understanding of forces in three dimensions, care should be taken to ensure that the Balder ride is complemented by other, more three-dimensional rides. The webpages of our Amusement Park Science project [6] include physics tasks of mixed degrees of difficulty for most of the rides at Liseberg.

The analysis of student learning during a course involving the amusement park project will be presented in a separate paper [7], with pre- and post-testing using the Force Concept Inventory, 'FCI' [8], supplemented with additional questions.

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References

[1] See Imego www.imego.se/. The 'product' page includes a more detailed description of 'Imego's micro motion tracker' and its possible uses.
[2] Pitch, Yaw, and Roll Systems liftoff.msfc.nasa.gov/academy/rocket_sci/shuttle/attitude/pyr.html
[3] The Internet Roller Coaster Poll www.geocities.com/wcoasterpoll/
[4] Stengel W 2003 Wooden rail for a ride as well as a method for fabricating and mounting such a wooden rail *US Patent* 6,550,393
[5] See e.g. Bakken C 2005 *Physics/Science/Math Days @ Paramount's Great America* physicsday.org
[6] Pendrill A-M 2005 *Science in the Liseberg Amusement Park* fy.chalmers.se/LISEBERG/eng/
[7] Partial results were presented at the *8th Nordic Conference on Science Education (Aalborg, 2005)*
[8] Hestenes D, Wells M and Swackhamer G 1992 Force Concept Inventory *Phys. Teacher* **33** 141–58
Halloun I, Hake R, Mosca E and Hestenes D 1995 password protected at modeling.la.asu.edu/R&E/Research.html

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