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Note: Planetary gravities made simple: Sample test of a Mars rover wheel

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We introduce an instrument for a wide spectrum of experiments on gravities other than our planet’s. It is based on a large Atwood machine where one of the loads is a bucket equipped with a single board computer and different sensors. The computer is able to detect the falling (or rising) and then the stabilization of the effective gravity and to trigger actuators depending on the experiment. Gravities within the range 0.4 g–1.2 g are easily achieved with acceleration noise of the order of 0.01 g. Under Martian gravity, we are able to perform experiments of approximately 1.5 s duration. The system includes features such as WiFi and a web interface with tools for the setup, monitoring, and data analysis of the experiment. We briefly show a case study in testing the performance of a model Mars rover wheel in low gravities. Published by AIP Publishing. [http://dx.doi.org/10.1063/1.4998261]

Setting up experiments at gravities other than Earth’s is a complex physics and engineering problem. Several approaches are established, but most of them are impractical for frequent use.1 Goldman and Umbanhowar and Altshuler et al. developed an experimental setup based on an Atwood Machine for studying the penetration of intruders into granular media.2,3 More recently, Sunday et al. have set up a facility inspired in the same principles of previous work that has shown a good performance for effective gravities (g eff) in the range 0.01 g–0.1 g.4 There are other approaches that use a centrifuge machine for induce artificial gravities greater than Earth’s.5

We have upgraded our former setup for gravity-controlled experiments, originally published in 2014 for the specific case of low velocity collisions into granular matter.6 We call it Lab-in-a-Bucket, a simple solution for a wide spectrum of experiments that may require to vary the gravity. Our instrument uses the same mechanical principle but includes different kinds of sensors and software tools that allow us to customize and execute the experiments. It is also possible to track moving objects inside the capsule and to add new sensors or actuators anytime using the most common communication interfaces. We illustrate a concrete application to planetary exploration by the inclusion of a setup to test the performance of a model Mars rover wheel in low gravities.

We first present an overview of the system. Then the physical principles used for varying the gravity are explained. Next we describe the measures we are able to perform and the event triggers we can shoot. Finally we show other features of the system allowing us to easily customize and perform the experiments.

The system is based on an 15-m tall Atwood machine where one of the loads is a bucket equipped with laboratory measurement tools and the other one is the counterweight for adjusting the acceleration of the whole system, see Fig. 1. The instrument contains a single board computer able to read data from any sensors deployed inside the bucket. The system is compatible with sensors and actuators that implement USB, I2C, SPI, or UART communication protocols. The instrument creates a WiFi network to setup and monitor the experiments. We also provide software tools for real-time data processing and post-processing that are explained next.

The effective gravity “felt” inside the bucket, g eff, can be calculated as the difference between the gravitational acceleration at the Earth’s surface and that of the bucket relative to the ground. While the bucket is on the move, we can control g eff by changing the mass of the counterweight following the formula,

\[ g_{\text{eff}} = g \left[ 1 - \frac{m_b - m_{cw}}{m_b + m_{cw}} \right] \] (1)

where \( g \approx 9.8 \text{ m/s}^2 \), \( m_b \) is the mass of the bucket, and \( m_{cw} \) that of the counterweight.

Figure 2 shows the data of an experiment where g eff has been set at 0.4 g. Notice that the actual effective time of the experiment is 1.31 s which is less than the maximum time (2.26 s) obtained using theoretical calculations. This is caused by not considering the time lapses spent on the stabilization of the desired g eff, or for stopping the moving bucket before it reaches the ground (or the pulley if it moves upwards in order to get g eff > g). This time difference is the price we pay for the accuracy of g eff while the bucket is moving.

The electronics of the instrument was designed from scratch, using only the pulley and the plastic bucket of the original setup presented by Altshuler et al.3 We added a single board computer able to log and process data in real time. We included different kinds of sensors fixed at the top of the bucket as shown in Fig. 3. Three axis acceleration and gyro data are sampled using a MPU-6050.6 Pressure and temperature inside the capsule are measured using a BMP1807 and for the magnetic field we use a HMC-5883L.8 The computer acquires data...
from the sensors every 8 ms, and the camera sensor is sampled at 25 fps in a 800 × 600 pixel resolution. Until the experiment ends, the data are temporally stored in RAM due to the writing latency imposed by the external storage devices. We use a 5 V powerbank to feed the computer and the sensors but we also include a 12 V Lithium battery to power up higher consumer devices, like motors, that may be used in particular setups.

As long as the experiment takes place, the information stored in RAM may be used by other software running on the computer. An example is the real-time algorithm we use to determine the stabilization of $g_{\text{eff}}$ using the measurements obtained by the accelerometer in the z-axis. Once the experiment ends, all the information is stored on a SD memory plugged in the computer.

Additional experimental information can be obtained by post-processing the data stored on the SD memory. For example, running a tracking algorithm over the camera images may return a function that describes the position of a moving object inside the bucket.

Reacting to time events is a key feature in experiments with limited duration. We have defined two types of digital signals to optimize experimental control: Start Triggers and Stop Triggers. Launching the Start Trigger typically indicates the beginning of the experiment’s effective time. It can be generated by external computers connected through the wireless network, by automatically detecting the stabilization of $g_{\text{eff}}$ or by any other convenient time event, we may be able to capture. The Start Triggers can be connected to the actuators’ interface shown in Fig. 3. Stop Triggers often imply the end of the experiment. It can be shot when a certain amount of time passed after the Start Trigger, but can also be generated by an external computer or by the end of the $g_{\text{eff}}$ stable period.

We designed an algorithm based on a state machine, guided by thresholds in the statistics of the z-axis acceleration signal, to automatically detect in real-time the $g_{\text{eff}}$ stabilization. Every single sample of the signal may be classified into one of the following experiment states according to the bucket motion: Stopped, Starting, Stable, and End. The first sample tagged in the Stable state (i.e., when the desired $g_{\text{eff}}$ stabilizes) may unleash the Start Trigger; the same way the first sample tagged in the End state may unleash an Stop Trigger.

In order to easily manage the setup of the experiments, we developed a web based control interface. It is possible to watch what happens inside the bucket in a real-time preview of the camera and sensor values. Every experiment gets tagged with the name, description, and date. We can choose the sensors and actuators to be used and the trigger’s configuration. When an experiment is completed the data obtained are stored in a file and compressed. Then the sensors’ data and video recorded by the camera are shown, providing a quick overview of the results. We can watch again the results of previous experiments and download the data in different formats.

The protocol of a typical experiment performed with our instrument consists in 6 steps. First, we fill the counterweight with the proper mass to get the desired $g_{\text{eff}}$. Second, we power-on and check the electronic devices inside the bucket. Third, we set the triggers and the desired configuration parameters for the experiment on the web interface using the WiFi network. Fourth, we place both loads on the Atwood machine and hold the pulley until the oscillations stop. Fifth, we start gathering data and then release the pulley. Finally, we stop the movement of the bucket and download the sensor and video data from the web for analysis.
FIG. 4. Sketch of the bucket equipped with the rover wheel and the granular media. The wheel moves on the sand describing a circle around the vertical symmetry axis of the bucket.

Mars has been on the spotlight of the aerospace research for decades. NASA, for example, has sent rovers to study the planet. The granular nature of the planet’s surface, combined with low gravity, imposes special challenges to the motion of rovers which are worth studying in detail.

With our instrument, it is possible to recreate an appropriate environment to study the rover’s wheel performance. Inspired by the NASA rover Opportunity, we 3D printed a scaled-down wheel and placed it inside our system to test its performance over Cuban sand at an effective gravity like that on Mars. Figure 4 sketches the setup for this particular experiment.

We process the images taken with the camera at the top to quantify the “effective rotation” of the wheel based on the motion of its center of mass. At the same time, we sample a Hall effect encoder placed in the motor holding the wheel to calculate the rotation of the wheel around its axis. Figure 5 shows sample measurements made of the wheel’s angular position obtained by the two methods. Further results in the analysis of the wheel’s performance will be published elsewhere.

We have presented a flexible experimental setup that allows the performance of a wide spectrum of experiments at controllable gravities, during short periods of time. The instrument shows a good performance reproducing effective gravities from 0.4 g to 1.2 g. We illustrate the capabilities of our instrument by measuring the performance of a miniature rover wheel over granular media at an effective gravity similar to the one found on Mars.

FIG. 5. Measurements of angular position of a rolling wheel over granular media at 0.4 g using two different methods. While the odometry quantifies the rotation of the wheel around its axis, the camera tracking measures the “effective rotation” of the wheel based on the motion of its center of mass. Then, the graph indicates slippage on the sand surface starting slightly before 6.4 s.

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