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The Augmented Laboratory – 3D, Multiple Object Tracking

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Abstract. We discuss the three dimensional, multiple object tracking capabilities of the “Augmented Laboratory”, a custom hardware and software setup we created for this purpose. Overall it proves to be a powerful and useful educational tool, not only allowing to use tracking in many more experiments with respect to traditional video tracking, but also creating 3D visualizations of the experiments themselves and of the tracking results. The setup was also tested with a group of aspiring teachers and their comments were here discussed.

1. Introduction

The “Augmented Laboratory” setup is a custom hardware and software setup we created for three dimensional, multiple object tracking [1]. It is based on the capability of obtaining 3D reconstructions of the physical world around us. These reconstructions can be visualized both live and as interactive playbacks. The software, entirely designed and coded by the author, simply requires a common computer and a Microsoft Kinect, which acts as a low-cost 3D camera. The setup can be used to obtain 3D reconstructions of scientific experiments.

It is here shown how such reconstructions can be very useful in motion experiments: in fact, following a simple procedure, the software is able to track the trajectories of the objects we are interested in. It is then possible to visualize the measured trajectories as well as all the important information that can be derived from them (energies, linear and angular momentum, the center of mass of the system, and so on). Watching the playbacks, it is possible to analyze this data step by step and to focus on important moments of the experiments, for instance a collision. All the gathered data can also be exported to be analyzed by external software such as Excel. The setup was tested with a group of university students who aspire to become physics and mathematics teachers, and their feedbacks are here analyzed.

2. 3D reconstructions of physical environments

The *Augmented Laboratory* is based on the capability of obtaining 3D reconstructions of the physical world. This can be done using a 3D camera. With this term, we here refer to any device which may provide a *depth image* or *depth matrix*: instead of providing information regarding colors, as a conventional RGB camera, these cameras provide information of the distance of the objects in front of them. See for example Figure 1, right: in this figure a depth image is represented, where brighter colors correspond to objects closer to the camera, while darker ones to more distant objects.

For this setup we chose the Microsoft Kinect device (v2), the first version of which was already introduced in [2] as a 3D camera for motion tracking. In principle, any 3D camera can be used in the same setup, with only minor changes to the software (although the peculiar characteristics of each different device would require testing and special care). The Kinect is placed over the environment we would like to reconstruct, for example using a simple setup as in Figure 1, left, or a ceiling mount. A black and white version of a depth matrix is represented in the same image to the right. The data acquisition code is based on the open source library OpenKinect [3].



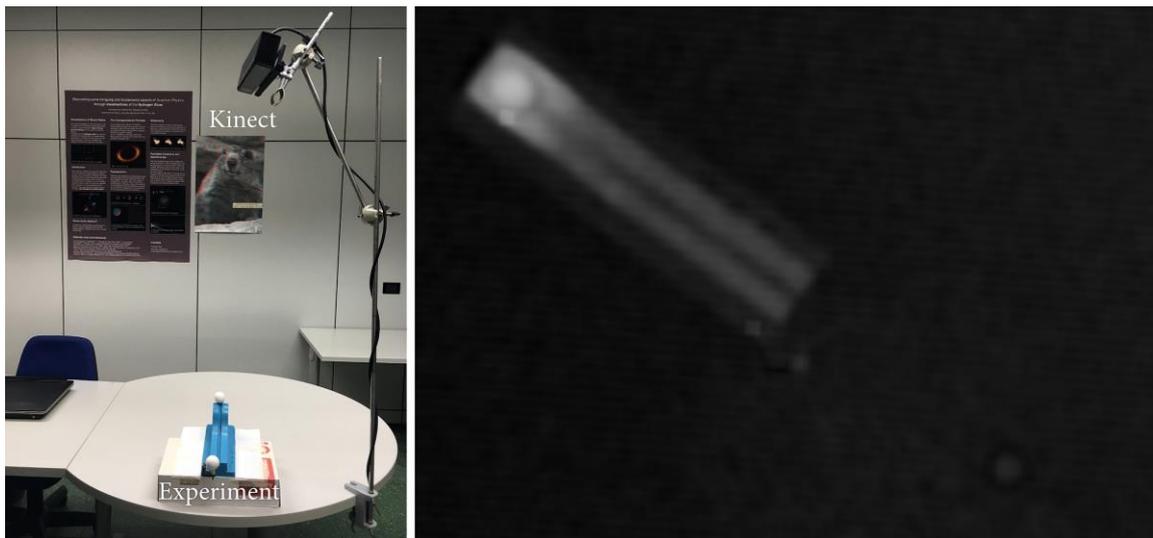


Figure 1. (Left) The Kinect is positioned above the environment we would like to reconstruct. (Right) An example of a depth matrix is here visualized as a black and white image, where brighter colors correspond to smaller distances between the sensor and the objects.

2.1. From depth matrices to 3D reconstructions

The simplest 3D visualization of a depth matrix is its *point cloud* representation. The idea is to represent each element of the matrix as a point correctly placed in a 3D virtual space. What is needed is then a transformation from (x, y, z) , the x and y coordinates of the element in the matrix and its depth value z , to (x', y', z') , the coordinates in the 3D virtual space.

The relation between z and z' depends on the linearity of the sensor and on the pre-processing done by the device. For our uses it was enough to trust the declared linearity of the Kinect v2 (giving 500-4500 depth values corresponding to 0.5-4.5 meters) and simply assume $z' = z$. For more accurate measuring tests should be done for each single device used (in principle each Kinect could give slightly different results given by fabrication issues).

The equations for x' and y' are:

$$x' = \left(x - \frac{res_x}{2}\right) \tan\left(\frac{fov_x}{2}\right) \frac{z}{2 res_x}$$

$$y' = \left(y - \frac{res_y}{2}\right) \tan\left(\frac{fov_y}{2}\right) \frac{z}{2 res_y}$$

where res_x and res_y are the width and height of the depth matrix respectively, and fov_x and fov_y are the horizontal and vertical *field of view* of the camera. For an extensive example of these relations used with the Kinect v1, see [2].

With these transformations it is possible to take all the elements of any depth matrix and represent them correctly in a 3D virtual space as a *point cloud* (Figure 2, left). It may also be convenient to represent the *point cloud* by filling the space between the points, thus obtaining a more natural look of the visual representation of the data. If the sensor also has a color camera, as is the case of the Kinect, it is possible to merge the color and the depth streams in a single visualization (Figure 2, right). There are many software and libraries that help creating such visualizations: for this project, the *Processing Java* library was used [4].

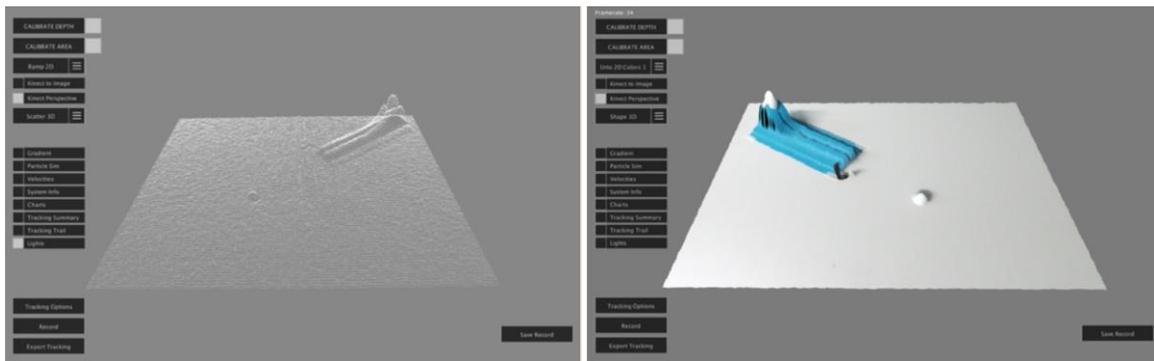


Figure 2. (Left) Point cloud visualization of a depth matrix. (Right) The same data represented using a 2D mesh to connect the points and also with the color information added.

2.2. Multiple object, three-dimensional motion tracking

For this project we are interested in tracking some objects used in motion experiments. We therefore need a way to distinguish them from the background. In order to do so, we used the following solution. Pressing a single button (or a key on the keyboard) a “base depth calibration” process starts, meaning that for several seconds the software acquires all the depth matrixes and calculates their arithmetic mean in order to suppress noise. This result will be used as a *reference matrix* containing all the information about the background. From now on, any added object may be identified. In fact, after the calibration process all the subsequent depth matrixes will be compared to the reference matrix, making the system able to recognize all the elements regarding the added objects.

A *naïve* implementation of this recognition algorithm would lead to many false recognitions, because of noise and artefacts. Two filtering processes have been adopted to overcome these difficulties. First of all, matrix elements differing from the reference values for less than a user-defined threshold value are ignored. Secondly, each cluster of adjacent elements (a candidate recognized object) will be ignored unless it contains a number of elements greater than another user-defined threshold value. At this point, all the information needed to track the objects is known. Any experiment may be performed and the objects we want to track are recognized in real time. Also, as already mentioned, everything may be recorded so that interactive playbacks may later be re-played. A large number of additional information derived from the trajectories may be displayed, such as velocity vectors, the center of mass of the system, plots and values regarding energies, momenta, and so on (both live and in the playbacks), as may be seen in Figure 3.

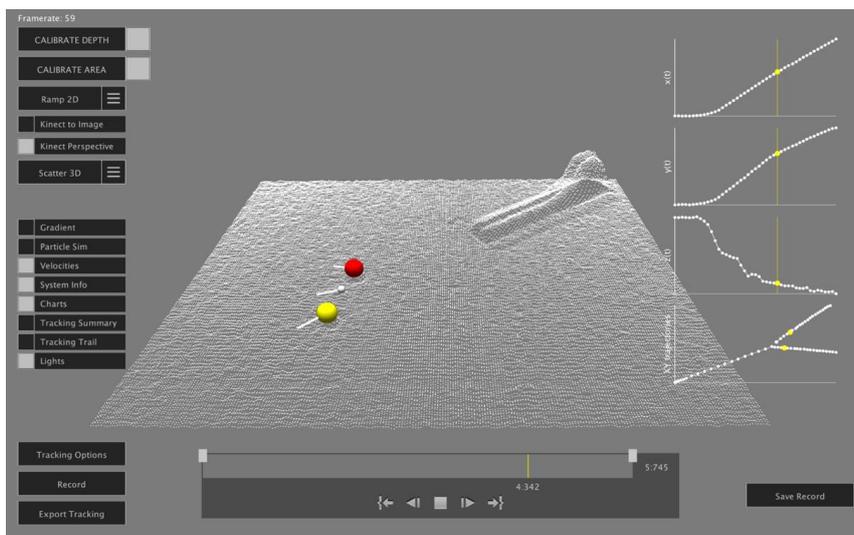


Figure 3. A screenshot of an interactive playback of a 3D reconstructed experiment regarding a collision between two spheres. The center of mass of the system is represented as a small white sphere. Velocity vectors and plots regarding the trajectory of the center of mass are also visualized.

3. Testing the setup with two motion experiments

We now present the results of two experiments reconstructed and analyzed with our setup. These experiments were chosen in order to allow us to discuss fundamental quantities such as linear momentum, angular momentum, kinetic and potential energies, and also in order to allow us to take full advantage of the 3D tracking capability of the setup. In fact, the choice of experiments is strongly limited when performing traditional 2D video tracking activities, whereas we are not. As already mentioned, we are interested in obtaining values for linear and angular momenta, potential and kinetic energies of the system, obtained from the measured trajectories. There are many sources of uncertainty regarding the measured positions, some regarding the hardware itself and others pertaining the object tracking algorithms implemented in the software. For this reason, we use statistical uncertainties given by regressions and averages.

3.1 Experiment 1: quasi-elastic collision

The first experiment is a collision between two spheres which then fall under the influence of the gravitational field. The first sphere is accelerated by a grooved track (Figure 4, left), while the second one is placed in such a way that the collision happens right after the first one leaves the track. The two spheres must have the same vertical position during the collision (a way to verify this is by checking if they hit the ground at the same time by listening to the sound of their first bounce). Also, experiments with different impact parameters may be performed.

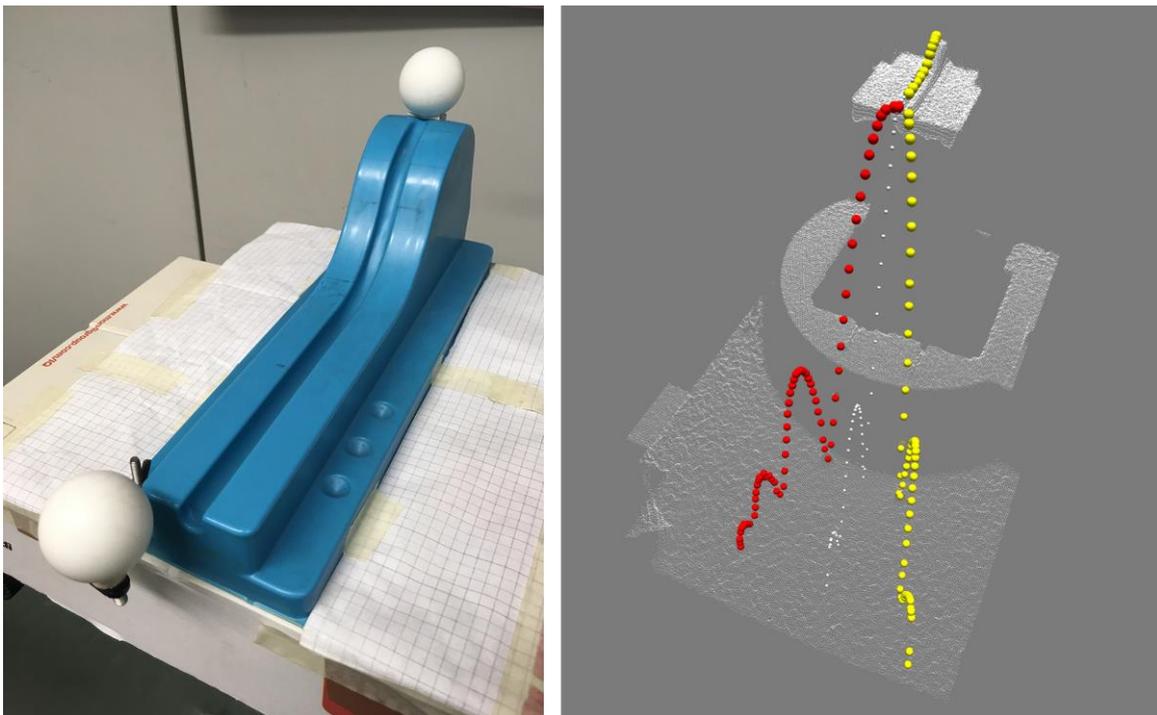


Figure 4. (Left) Experimental setup. (Right) Three dimensional visualization of the tracking results. The small white dots in the middle represent the trajectory of the center of mass.

The spheres have a diameter of about 3 cm, and masses $m_1 = (18.20 \pm 0.01)$ g and $m_2 = (18.28 \pm 0.01)$ g. In Figure 4, right, a visualization of the measured trajectories, together with the trajectory of the center of mass, is shown, and as expected they look like parabolic ones. This is also well seen in the measurements. In fact, the z positions of the center of mass (the z -axis is chosen as normal to the floor) are well fitted by a quadratic time dependence (Figure 5, left). Also, regression analysis leads to a value of the gravitational acceleration of $g_m = (10.0 \pm 0.3)$ m/s². The three dimensional nature of the data allows us to also look at the trajectories from the above, meaning projecting the trajectories on the xy -plane. We therefore look at the values of linear momentum before and after the collision obtaining, respectively, $P_0 = (32 \pm 1) \times 10^{-3}$ kg m s⁻¹ and $P_f = (31 \pm 2) \times 10^{-3}$ kg m s⁻¹. The corresponding angles

between the direction of \mathbf{P} and of the x -axis are $\square_0 = 14^\circ \pm 1^\circ$ and $\square_f = 15^\circ \pm 1^\circ$. We can conclude that such measurements are consistent with the expected conservation of momentum. By assuming a perfectly elastic collision between friction-less and rotation-less masses one expects to obtain a scattering angle of 90° : the observed value is $88^\circ \pm 1^\circ$. We are also able to calculate the averages and standard deviations of the energy of the system both before and after the collision. As expected, the resulting loss of energy is below the measurement uncertainty, with initial and final values being $E_0 = (0.63 \pm 0.01)$ J and $E_f = (0.64 \pm 0.02)$ J, respectively.

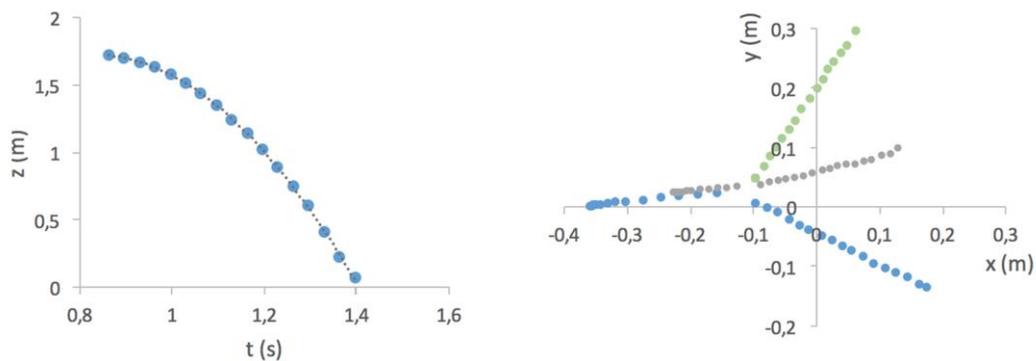


Figure 5. (Left) z coordinate of the center of mass after collision and before bouncing. (Right) Trajectories of the two balls and of their center of mass (grey dots) along the xy -plane, meaning as seen from the above.

3.2 Experiment 2: bolas

For this experiment, we created a *bolas* (a throwing weapon made of several balls connected by strings) using a nylon line and 2 spheres (Figure 6, left). The spheres had masses $m_1 = (9.44 \pm 0.01)$ g, and $m_2 = (9.48 \pm 0.01)$ g. We threw the bolas making it spin and tracked its motion. The resulting motion is the superposition of the motion of the center of mass and the rotation of the spheres around it (Figure 6, right). As in the previous experiment, the center of mass follows a parabolic trajectory (Figure 7, left) and from it we obtain a value of the gravitational acceleration of $g_m = (9.6 \pm 0.2)$ m/s².

In Figure 7, right, the circular trajectory relative to the center of mass of the two spheres is shown. Measurements are consistent with the expected conservation of angular momentum, showing relative fluctuations of about 10% around the mean value: $L = (1.9 \pm 0.2) \times 10^{-3}$ kg m² s⁻¹. Similarly, measurements are consistent with the conservation of energy, with relative fluctuations of about 3% around the mean value $E = (16.5 \pm 0.5)$ J.

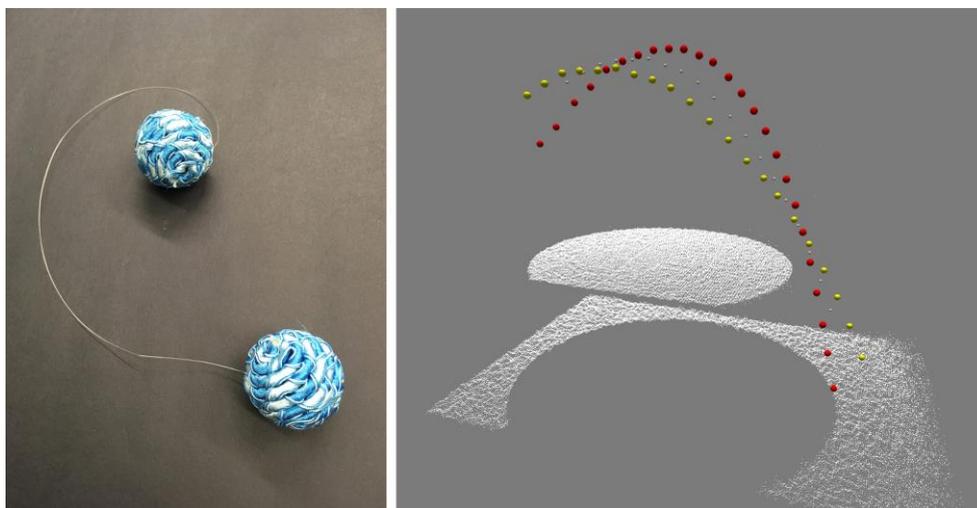


Figure 6. (Left) The bolas used in this experiment. (Right) Visualization of the measured trajectories of the two spheres and of the resulting center of mass (smaller white spheres).

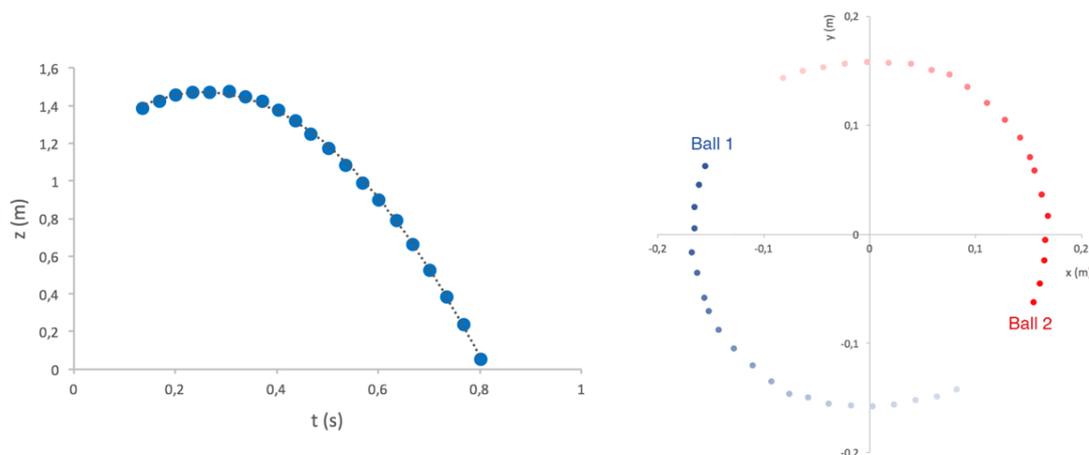


Figure 7. (Left) Trajectory of the center of mass. (Right) Trajectories of the two spheres relative to the center of mass of the bolas (clockwise rotation).

3.3 Testing the setup with aspiring teachers

We tested the *Augmented Laboratory* with a group of 15 university students who aspire to become physics and mathematics teachers. They previously used video analysis software, in particular *Tracker* [5], to perform traditional 2D tracking. At the end of the experience they were given a survey asking for feedbacks regarding the use of 2D/3D tracking systems.

Overall, they were enthusiastic about the use of these systems (both *Tracker* and the *Augmented Laboratory*) and they claim they would certainly use them in class:

“Both Tracker and the 3D apparatus look like very good tools. We can replay the performed experiments as many times as we choose while also looking at the graphs about the physical quantities we are interested in. I would certainly use both in class”

Some of them were particularly impressed by the 3D tracking capabilities, because of the different motion experiments that can be done with it and also for motivational reasons:

“Undoubtedly the capability of performing a 3D tracking allows to get motion data of objects which are not following a planar trajectory”

“Upsides of the 3D tracking: it’s wonderful and allows to get measurements, even for complicated experiments, easily and immediately”

“From an educational point of view the setup which allows 3D tracking may be more interesting and therefore help the students’ involvement”

The only reported reason to prefer a 2D motion tracking system is that it can simply be enough from an educational point of view:

“The 3D tracking is better than the 2D tracking because of the complexity of the motions that can be studied, but generally speaking, I think the 2D tracking is enough”

“...the 2D abstraction of the dynamics of a body is generally used in secondary schools, and maybe even universities”

Some of them suggest the use of both systems in order to get all of their advantages, as they may be seen as complementary in some tasks:

“I believe that for simple phenomena such as carts collisions and similar, I would prefer to use Tracker [...] But the 3D tracking system can then be used at the end of the course”



Figure 8. Testing the setup with aspiring teachers.

4. Conclusions

We presented the tracking capabilities of our system, the “Augmented Laboratory”. Overall it proved to be a powerful and useful tool for 3D, multiple object tracking. Not only does it allow the use of tracking in many more experiments than those which are usually done with traditional video tracking, but it also creates 3D visualizations of the experiments themselves and of the tracking results. These features may have great value for educational purposes. The setup was also tested with a group of aspiring teachers, which were enthusiastic about it and their comments were here discussed.

5. References

- [1] Rosi T et al 2017 Multiple object, three-dimensional motion tracking using the Xbox Kinect sensor. *Eur. J. Phys.* **38**, 6. DOI: 10.1088/1361-6404/aa8183
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- [5] “Tracker” website: Tracker website: <http://physlets.org/tracker/>