2025 Online Physics Olympiad: Invitational Contest



Part II

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Experimental Question [15 marks]

Ball Knowledge [15 marks]

Lionel finds himself on an unknown planet, with only a very precarious camera of fixed frame rate and a spherical football with him. He feels that the air is weird and that gravity is too, so he decides to put his skills to use and starts kicking his ball and recording the trajectory it makes with his camera. The football has a radius of $r = 11$ centimeters and a mass of $m = 430$ grams. Let the drag coefficient be $C_d = 0.47$. Despite his high skill, Lionel is still human; therefore, there will be some uncertainty in the speed, angle and angular speed he imparts on the ball.

The following equations determine the forces experienced by a ball traveling in the air:

$$\vec{F}_{\text{drag}} = -\frac{1}{2}\rho C_d A v^2 \,\hat{v}$$

$$\vec{F}_{\text{Magnus}} = Kr\vec{\omega} \times \vec{v}$$

where ρ is the air density, A is the cross sectional area of the ball, $\vec{v}$ is the ball's velocity, $\vec{\omega}$ is the ball's angular velocity, and K is the Magnus force coefficient. The angular deceleration felt by the ball is given by

$$\dot{\omega} = -B\omega v.$$

Explanation of the simulation program. The executable files are found in this Google Drive folder. Please select the folder that corresponds to the operating system of your computer. For Linux and Windows, simply download the executable file ("magnus.bin" or "magnus.exe", respectively) inside. For MacOS, download the file "magnus.zip", then double-click it to create the file "magnus_sim.dist". Right-click on "magnus_sim.dist" and select "Show Package Contents" to reveal the folder's contents; inside, locate the executable file "magnus". Do not delete any of the other files in the package!

Double-click the executable to run. You may have to temporarily disable your local malware-blocking software. On MacOS, if your computer blocks the opening of the executable, navigate to System Settings and go to Privacy & Security. Below Security, there should be a notification that "magnus" is trying to be opened; click "Allow anyways" or "Open anyways".

Please note that the executable may take a few moments to load. It will prompt you for the following quantities:

- Initial speed v_0 in m/s, restricted to the range [5 m/s, 40 m/s]; the uncertainty in v_0 is of order 0.5 m/s.
- Initial angle of launch θ_0 in degrees, restricted to positive θ_0 only; the uncertainty in θ_0 is of order 0.5°.
- Initial angular velocity ω_0 in rad/s, restricted to the range [-400 rad/s, 400 rad/s]; the uncertainty in ω_0 is of order 1 rad/s. Only angular velocities perpendicular to the trajectory are allowed in the simulation. The initial angular velocity ω is positive when the ball is given underspin and is negative when the ball is given topspin.
- The desired name of the output text file, such as "output.txt".

The executable will then provide you with the location that the output file has been saved at. If you have trouble finding the output file, paste the location of the file's folder into the URL bar of your file explorer (in Mac Finder, use Cmd+Shift+G).

The output text file will contain the data points (x,y) of the ball's trajectory that the camera captures, in chronological order. The executable will then ask you if you would like to run the simulation again.

If you wish, you may also use this Jupyter notebook to plot the trajectory. Make a copy of the notebook, and copy the output file's text into the indicated portion of the notebook's code.

Your task is to find the following quantities, with uncertainties, to the highest accuracy that you are able to. Provide all data, tables, graphs, and/or intermediate quantities you use.

- wind speed v_w [2 pts]
- air density ρ [2.6 pts]
- gravitational acceleration g [2.6 pts]
- camera frame rate r_c in Hz [0.8 pt]
- Magnus force coefficient K [3 pts]
- inertial coefficient B [4 pts]