Falcon 9 landing kinematics

FizziQ activity · High school · 35 min

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Students track a Falcon 9 first stage frame by frame in FizziQ's kinematics module on smartphone or tablet, plot velocity and analyse the braking burn strategy.

Learning objectives

- Analyze the descent and landing of a Falcon 9 rocket using video-based kinematic tracking
- Determine the velocity and acceleration profiles during the landing sequence
- Identify the distinct phases of the descent: atmospheric entry, main braking burn, and final landing burn
- Understand the concept of a suicide burn and why it minimizes fuel consumption
- Connect kinematic analysis to real aerospace engineering challenges

Instruments and sensors

Video (kinematics) analysis module

Materials

- Smartphone or tablet with the FizziQ application
- Falcon 9 rocket landing video (available via the FizziQ map link or video library)
- Information on the size of a Falcon 9 rocket (about 70 meters, first stage including legs)
- FizziQ experiment notebook
- Note: the protocol remains adaptable to any comparable video analysis tool.

Protocol

1. Open FizziQ and navigate to the Kinematics module. Load the Falcon 9 landing video from the FizziQ map link or video library.
2. Set the scale using the known height of the Falcon 9 first stage: approximately 70 meters (including legs).
3. Define the origin at the landing pad with the y-axis pointing upward.
4. Track the base of the rocket frame by frame through the descent sequence. Start from the highest visible point.
5. Collect as many data points as possible, especially during the final 10 seconds before landing when changes are most dramatic.
6. Plot the altitude versus time graph. It should show a steep descent that sharply levels off just before touchdown.
7. Calculate the velocity at each time step from the position differences. Plot velocity versus time.
8. Identify the braking phases: the velocity should decrease in distinct stages, with sharp changes when engines ignite or shut down.
9. Calculate the deceleration during the main braking phase. Compare with the acceleration of gravity (9.81 m/s²).
10. Note that the deceleration must exceed g for the rocket to slow down (the net deceleration is a_thrust - g).
11. Estimate the velocity at engine ignition and the time from ignition to touchdown. Verify that these are consistent with a constant-deceleration model.
12. Discuss: why does SpaceX use a last-second suicide burn rather than a gradual, gentle descent? What are the advantages in terms of fuel efficiency?

Expected results

The Falcon 9 first stage descends at high speed (100-300 m/s) before the main braking burn, which produces a deceleration of 20-40 m/s² (2-4g). The final landing burn brings the velocity from about 20-30 m/s to zero in the last 5-10 seconds. The altitude-time graph shows a characteristic hockey-stick shape: nearly linear (constant velocity) during free descent, then sharply curving as the engines fire. The velocity-time graph shows distinct phases with abrupt transitions. Pointing accuracy in the video analysis is limited by the rocket's distance from the camera, typically giving velocity precision of ±5-10 m/s. Students should observe that the deceleration during the landing burn must be significantly greater than g to overcome both gravity and the existing downward velocity.

Questions

- Why must the rocket's deceleration exceed g during the landing burn?
- What is a suicide burn, and why is it more fuel-efficient than a gradual descent?
- What would happen if the engine ignited one second too late? One second too early?
- How does SpaceX control the rocket's attitude (orientation) during descent?
- What role do the grid fins play during the atmospheric descent phase?
- How does the mass of the rocket change during the landing burn, and how does this affect the deceleration?

Going further

- Compare the descent profiles of different Falcon 9 landings to see how consistent the approach is
- Analyze a failed landing attempt and identify what went wrong from the kinematic data
- Calculate the fuel consumption during the landing burn from the known engine thrust and burn time
- Compare the Falcon 9 landing profile with that of a lunar lander (Apollo) using historical data
- Model the suicide burn mathematically: given an initial velocity and maximum thrust, calculate the optimal ignition altitude