AIAA

AEROSPACE MICRO-LESSON

Easily digestible Aerospace Principles revealed for K-12 Students and Educators. These lessons will be sent on a bi-weekly basis and allow grade-level focused learning. - AIAA STEM K-12 Committee.

ROCKET SCIENCE 102: GUIDANCE AND STABILITY

Once you have enough thrust to launch a rocket into the air, how do you keep the front end pointing forward and get the rocket to where you want it to go? It turns out that these are not simple things. This lesson explores these problems, some solutions, and some pitfalls encountered while finding out the solutions.

Next Generation Science Standards (NGSS):

- Discipline: Physical Science.
- Crosscutting Concept: Scale, Proportion, and Quantity.
- Science & Engineering Practice: Developing and using models.

GRADES K-2

NGSS: Motion and Stability: Plan and conduct an investigation to compare the effects of different strengths or different directions of pushes and pulls on the motion of an object.

Try balancing a stick vertically on your fingertip. It's not that easy, is it? You have to move your hand back and forth and from side to side to counteract the tendency of the stick to tip over. Often, when you have moved your hand one way to stop the stick from tipping in that direction, the stick will promptly start to tip over in the opposite direction.

Rocket designers face the same problem. When a rocket launches from the surface of the earth, its engines are supporting it from the bottom. If the rocket is not balanced perfectly over its engines, it will start to tip; even if it is balanced perfectly, a gust of wind or an imbalance in the thrust of the engines will make it start to tip. To counteract this tipping, a rocket needs two things: something that can sense which direction it is starting to tip and something that can push the base of the rocket sideways to straighten it out. There was an unmanned Soviet rocket launch in which the stabilizing system did not work; you can find two videos of it here and here. (One video has freezing frames while the other is shot from much farther away; while neither one is the best possible, both are usable.)

Suggested Activity: Have the students try balancing yardsticks vertically on their fingers. Then have them try to balance rulers; they may be able to balance the yardsticks, but rulers will be beyond them. Try attaching a weight to the top of the yardstick and see if that makes it easier or harder to balance. Try balancing it with the weight at the bottom of the yardstick.

GRADES 3-5

NGSS: Motion and Stability: Plan and conduct an investigation to provide evidence of the effects of balanced and unbalanced forces on the motion of an object.

When launching a rocket into space, the mission planners need to know exactly where they want the rocket to go and what direction it needs to move in order to get there. This sounds easy but it is not. The first rocket mission to the Moon, for example, missed its target! The Soviet "Luna 1" mission, launched in January 1959, was supposed to hit the Moon but instead flew past it at an altitude of almost 4,000 miles and went into orbit around the Sun. How does one miss a target that is 2,000 miles wide? (The first American space probe to fly past the Moon, Pioneer 4, also missed its intended destination by about 30,000 miles; one source says it was a "trajectory error" while another says that it was because of an engine problem.) The answer is "very easily, if the target is 235,000 miles away." When sending a spacecraft to Mars or to another planet, the accuracy required is even greater; a trip to Mars requires traveling at least 33 million miles, and more likely something like 300 million miles, through space and when the spacecraft arrives it must be within a few tens of miles of its target for it to enter the correct orbit or to land in the right place.

While the accuracy required to deliver an interplanetary spacecraft—or even one going to the Moon—is very stringent, the equations that describe the spacecraft's motion are very well understood and it is possible to predict that motion very accurately. What the mission planners do, then, is to figure out the path they want the spacecraft to follow and then how long to fire the rocket—and in which direction—to set the spacecraft onto that path. Then they monitor the flight of the spacecraft through space and measure how far it drifts away from the desired path. Every now and then, the mission controllers will send a command to the spacecraft to fire its rocket for a specific amount of time in a specific direction to nudge the spacecraft back toward its desired path. These "midcourse corrections," as they are called, make it less important for the initial guidance of the rocket to be absolutely correct.

Suggested Activity: You can illustrate the principle of the midcourse correction out on a playing field. Have a student stand on one side of the field and select a target on the other side. Then let him (or her) cover his eyes and start walking toward the target. After he has taken twenty or so steps, shout "Midcourse Correction!" and let him uncover his eyes and adjust the direction he is walking to point toward the target again. Repeat the process until he reaches the target.

GRADES 6-8

NGSS: Motion and Stability: Plan an investigation to provide evidence that the change in an object's motion depends on the sum of the forces on the object and the mass of the object.

The problem of keeping a space-bound rocket pointed in the correct direction has two parts. The first part is keeping it pointed properly while the rocket is flying through the atmosphere; the second part is keeping it pointed properly while in space. In addition, since most of the mass of a rocket is its propellants (fuel and oxidizer), the mass and location of the center of gravity will change markedly as the rocket ascends. The control system needs to be able to handle all of these situations.

When a rocket is ascending through the atmosphere, fins near its back end will help keep it pointing forward. If the nose of the rocket tips in some direction, the air flowing past it will push on the fins and tend to push the tail back so that it is directly behind the nose and the rocket is moving straight forward again. This phenomenon is called "aerodynamic stability" and is not restricted to rockets; airplane tails and the tail feathers on darts have the same effect.

Aerodynamic stability, helpful though it is, is not powerful enough to counteract the perturbations on a full-sized rocket. Also, as the rocket gets higher in the atmosphere, the air becomes thinner (less dense) and loses its effectiveness in keeping the nose of the rocket pointing forward. To help the fins, rocket designers generally do one of three things. Either they have additional, small "vernier rockets" mounted sideways to push the nose and tail of the rocket back into alignment, they put vanes in the nozzle to steer the exhaust, or they mount the nozzles of the main rockets on gimbals to allow them to turn slightly.

Suggested Activity: Move a yardstick or other long object across a table by pulling on one end of it. Then move it across the table by pushing on its end. Notice how, when you are pulling the object will follow along in whatever direction you are pulling, but when you are pushing you need to keep adjusting what direction you are pushing in so that the object will stay in front of your push.

GRADES 9-12

NGSS: Motion and Stability: [Analyze data to support the claim that Newton's second law of motion describes the mathematical relationship among the net force on a macroscopic object, its mass, and its acceleration.]

Nowadays the positions of the planets are known very precisely. At the beginning of the Space Age, though, this was not the case. When the Mariner mission planners first approached astronomers asking for the positions of Venus and Mars, the answer came back as the angles required to point a telescope at the planets given to an accuracy of about a hundredth of an arcsecond and distances in terms of the Astronomical Unit, which is the average distance from the Earth to the Sun. Since an arcsecond is one sixtieth of an arcminute, which is one sixtieth of a degree, and since an object's distance is irrelevant to looking at it through a telescope, this was plenty of accuracy for any astronomical need. After flying one hundred million miles through space, though, an error of one hundredth of an arcsecond would put a spacecraft off course by almost five miles.

As bad as a five-mile miss is, that is not the biggest problem. The size of an Astronomical Unit, which formed the basis of all distance measurements in the Solar System, was not known to better than one part in ten thousand. Astronomers with their telescopes could measure angles very precisely, but measuring the distance to any astronomical body beyond the Moon is very difficult. While an error of one part in ten thousand is quite small, at a distance of one hundred million miles the resulting error is about ten thousand miles, which is more than the diameter of any of the inner planets. This simply was not good enough for the space mission planners.

Early in the Space Age, in 1964, scientists bounced radar waves off the planet Venus and timed how long it took for them to travel there and back again. This improved the accuracy of the measurement of the size of the Solar System by an order of magnitude, to about one part in 150,000. Measuring the trajectories of interplanetary spacecraft, knowing their speeds, and measuring the time required for radio transmissions to travel between them and the Earth has increased the accuracy further so that now we know the size of the Solar System (and the distances to the planets) to about one part in fifty billion. For something one hundred million miles away, that is an uncertainty of about ten feet.

With modern high-speed computers, planners of space missions can solve the equations of motion that describe a spacecraft's path through the Solar System directly. These equations account for the gravitational attraction on the spacecraft from the Earth, the

GRADES 9-12 (CONTINUED)

Moon, the Sun, and any other relevant astronomical bodies. Early in the Space Age, though, before powerful computers were developed, mission planners had to use approximations to allow them to solve the equations of motion.

The primary approximation that mission planners used is called the “patched conic” approximation. To use the patched conic approximation, one assumes that when the spacecraft is influenced primarily by one astronomical body the effects of all other astronomical bodies can be neglected. This simplifies the problem to a “two-body problem” which has an elliptical orbit as its solution. The ellipse is the “conic” of the “patched conic” approximation.

When the spacecraft passes from the influence of one astronomical body to another, its position and velocity at the point it makes the transition are used as the initial conditions for an elliptical orbit around the second astronomical body. This is the “patch” part of the “patched conic” approximation. This is not exact, obviously, but the gravitational attraction of the second body as the spacecraft is in orbit around the first body pulls in one direction, the gravitational attraction of the first body as the spacecraft is in orbit around the second body pulls in the opposite direction, and the two effects counteract each other. The errors introduced by the approximation are corrected by a mid-course correction (see above) after the spacecraft has moved beyond the transition point.

Sixty Years Ago in the Space Race:

February 21: The Soviet Union launched a single-stage sounding rocket carrying 3,340 pounds of scientific instruments to an altitude of 294 miles.

February 28: The American Department of Defense put the Air Force in charge of developing the nation's inter-continental ballistic missiles (ICBMs) and intermediate-range ballistic missiles (IRBMs).