Space Vehicle Control Systems

4.3.1

In This Chapter You'll Learn to...

- ☛ Describe the elements of and uses for control systems
- ☛ Explain the elements of space vehicle attitude determination and control subsystems and describe various technologies currently in use (enrichment topic)

Outline

Imagine you're a one-person spacecraft, flying the manned maneuvering unit out of the Space Shuttle's payload bay, as shown in Figure 4.3.1-1. Your mission is to fly to a crippled satellite and install a new black box. You must somehow manipulate the joy sticks in your hands to control your position, velocity, and orientation so you're lined up with the access panel on the spacecraft. How should you rotate? In which direction should you fire your thrusters? Do you speed up or slow down? Although this may sound like a fun scenario for a video game, we must answer these questions for nearly all spacecraft. In this chapter we'll begin by examining the basics of any control system and then see how we can apply this process to rotate a spacecraft in space.

Space Mission Architecture. This chapter deals with the Spacecraft segment of the Space Mission Architecture.

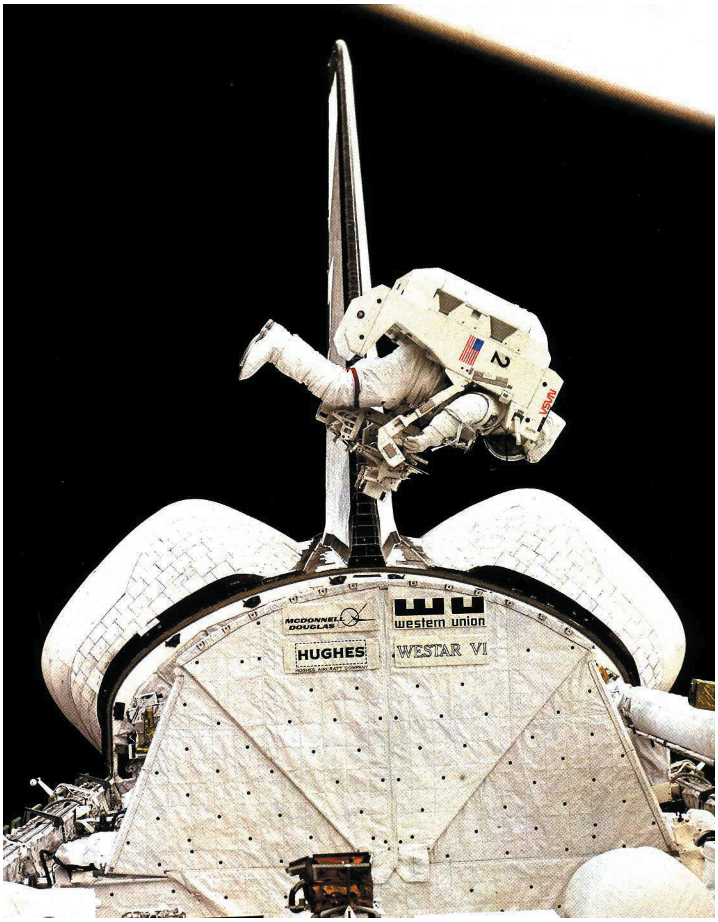


Figure 4.3.1-1. Space Vehicle Control. An astronaut flying the manned maneuvering unit (MMU) must carefully control rotation, position, and velocity to accomplish the mission (and not get lost in space!). *(Courtesy of NASA/Johnson Space Center)*

4.3.1.1 Control Systems

In This Section You'll Learn to...

- Describe the elements of a system
- Explain the difference between open-loop and closed-loop control systems and give examples of each
- Describe the steps in the control process
- Apply block diagrams to describe the functions of control systems

A *system* is any collection of things that work together to produce something. Systems have inputs (what goes in), outputs (what comes out), and some process in between that turns the inputs into outputs. In electronic systems, the inputs and outputs are called *signals*. The part of the system that performs the process is typically called the *plant*. The plant is usually an "equal-opportunity" processor that will respond to either precisely calculated inputs or random environmental inputs or both.

To simplify our discussion of systems, we like to illustrate them using *block diagrams*, in which lines represent input and output signals and boxes represent the plant or other components. Figure 4.3.1-2 shows the simplest type of system block diagram. For space-vehicle applications, the success or failure of the mission depends on the output of various subsystems. Therefore, we're most interested in a specific class of systems called *control systems*. Control systems are everywhere. If you've ever flushed a toilet, driven a car, or turned up the thermostat on a frigid winter night, you've used a control system.

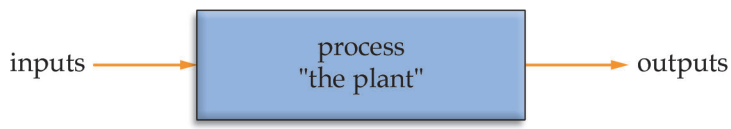


Figure 4.3.1-2. System Block Diagram. All systems take some input (or inputs), perform some process in the "plant," to produce an output (or outputs). We illustrate the functions of systems using block diagrams, in which input and output signals are shown as arrows and the plant, or other components, are shown as boxes.

Figure 4.3.1-3. A Simple Heating Control System. With the simplest type of heating control system, we throw logs on the fire and wait for heat to come out, warming the room. Unfortunately, such a simple system is "open-looped," so there is no guarantee we'll get the right amount of the desired output.

To understand how we use control systems, let's look at a problem we're all familiar with—heating a house. In the old days, people heated their homes only with fireplaces. They started with some desired result "It's too cold in here, let's warm things up!" and decided what action to take—"Throw some logs on the fire!" The logs burned, providing heat, and the house warmed up. We can draw a simple diagram for this whole process, as shown in Figure 4.3.1-3. As you can see, the input (logs) go into the fireplace and burn, which produces the output (heat).

Unfortunately, this simple control system has one major drawback. If you put on too many logs, the room can get too hot. And, when you went to sleep at night, there was no way to ensure the house would still be warm in the morning. A system that can't dynamically adjust the inputs based on what's actually happening is an *open-loop control system*. Of course, people lived with this kind of heating system for thousands of years (and still do). But eventually we got tired of waking to a cold house and invented the modern home-heating system. Let's see what makes this modern control system an improvement.

On cold winter nights, we turn up the dial on the thermostat to a desired temperature and wait for the heat. After some time, the furnace reaches its operating temperature, turns on its fan, and the room temperature starts to rise. When the house reaches the desired temperature, the furnace shuts off. Simple, right? But what's really going on here?

As with any control system, we have some desired result—a house at 20° C (75° F). This desire is what we tell the thermostat when we set the dial. For this example, the heating-control system has different jobs. First, it measures the current temperature in the house using a thermometer. In control-system lingo, the thermometer is a *sensor*, because it measures the output of the system. Next, the control system decides what to do using the "brains" of the thermostat. The "brain" of the thermostat is called the *controller*, because it compares the sensor output to the desired output and decides what type of input the system needs. If it's cold outside, the "environmental inputs" will eventually reduce the temperature in the house to less than 20° C (75° F). When this happens, the controller knows to turn on the furnace. Similarly, if the temperature is greater than 20° C (75° F), it knows to turn off the furnace. Finally, the furnace carries out the thermostat's decision by providing heat. We call the furnace an *actuator*, because it takes commands from the controller and produces the required output for the system. Figure 4.3.1-4 illustrates the various pieces of this control system.

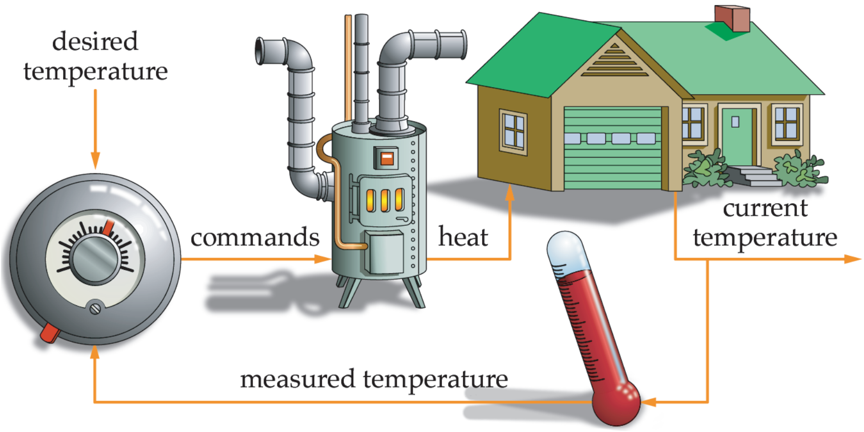


Figure 4.3.1-4. The Modern Home-heating System. A modern home-heating system continually measures the temperature and decides when to turn the furnace on or off.

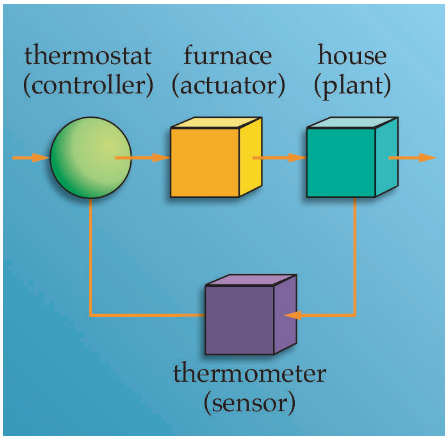


Figure 4.3.1-5. Block Diagram for a Heating-control System. It's easier to represent the elements of a control system

We call this type of system a *feedback control system* or a *closed-loop control system*, because we have a thermometer (sensor), which continually measures the current temperature and feeds this information back to the thermostat (controller). With this information, the thermostat produces the correct furnace (actuator) commands to maintain the house at 20° C (75° F), despite environmental inputs (close the window please!). Again, we can draw a simple block diagram to illustrate what's going on in this system, as shown in Figure 4.3.1-5.

In this simple example we've identified the four basic tasks all control systems must do

- *Understand* the system's behavior—how the plant will react to inputs, including environmental inputs, to produce outputs. This is also known as the *plant model*.
- *Observe* the system's current behavior—using sensors
- *Decide* what to do—the job of the controller
- *Do* it—using actuators

Closed-loop control systems, such as the heating system described above, are in cars, planes, spacecraft, and even the human body. They are extremely useful because, unlike open-loop systems, they can make a system do what we want even in the face of random environmental inputs.

On space vehicles, control systems are an integral part of virtually all payloads and subsystems. For example, a remote-sensing payload may need to control

- Exposure
- Aperture settings
- Lens-cover mechanisms
- Imaging time and duration

To support the payload, each subsystem in the spacecraft bus needs to control something as well

- Momentum (angular and linear)—the job of attitude and orbit control subsystem (AOCS)
- Data (bits and bytes)—the job of communication and data-handling subsystem (CDHS)
- Power (current, voltage, distribution)—controlled by the electrical power subsystem (EPS)
- Internal environment (temperature, air, water, food, waste)—the job of environmental control and life-support subsystem (ECLSS)
- Loads (bending, twisting, shaking)—handled by structures and mechanisms
- Rocket thrust (valves, pressure, temperature)—provided by the propulsion subsystem

In the rest of this chapter, we'll focus our attention on momentum control—angular and linear—the job of the *attitude and orbit control subsystem (AOCS)*. This is the "steering" function we described for the school bus in Chapter 11. As you can imagine, in operation the two functions of controlling angular and linear momentum often overlap. (In practice, it's difficult to change just angular momentum without having some effect on linear momentum—try spinning a frisbee without moving it!) However, for purposes of discussion here, we'll keep the two functions (angular and linear momentum control) separate. In Chapters 13 and 14 we'll return to the other subsystems to see their control systems in action.

Section Review

Key Concepts

➤ All systems take some input and complete some process to produce an output. Inputs and outputs are called signals, and the element doing the process is called the plant. We can best illustrate systems using block diagrams.

➤ The simplest type of control system is open-loop. Input produces an output. Unfortunately, open-loop systems can't dynamically adjust inputs to control outputs.

➤ Feedback control systems, also called closed-loop control systems, can better ensure we get our desired output because it can sense outputs (what we get), compare them to desired outputs (what we want), and adjust inputs as needed. Closed-loop control systems apply four steps

- *Understand* the system's behavior—how the plant will react to inputs, including environmental inputs, to produce outputs. This is also known as the plant model.
- *Observe* the system's current behavior—using sensors
- *Decide* what to do—the job of the controller
- *Do* it—using actuators

➤ Virtually all spacecraft payloads and subsystems rely on closed-loop systems to control

- Imaging, communicating, and operating other missions—payloads
- Momentum (angular and linear)—attitude and orbit control subsystems (AOCS)
- Data (bits and bytes)—communication and data-handling subsystem (CDHS)
- Power (current, voltage, distribution)—electrical power subsystem
- Internal environment (temperature, air, water, food, waste)—environmental control and life-support subsystem (ECLSS)
- Loads (bending, twisting, shaking)—structures and mechanisms
- Rocket thrust (valves, pressure, temperature)—propulsion subsystem

4.3.1.2 Attitude Control

In This Section You'll Learn to...

- ☛ Explain and apply important concepts in attitude dynamics to the problem of space vehicle control
- ☛ Describe key elements and technologies used in a space vehicle's attitude determination and control subsystems and explain them using block diagrams

We'll begin our discussion of the space vehicle's attitude and orbit control subsystem (AOCS) by focusing on the attitude part of the problem. Attitude defines a vehicle's orientation in space. For example, if we want a spacecraft to take pictures of a particular spot on Earth, we need to align the payload so it points at the spot. In this case, we'd need to control the spacecraft's attitude so it points "down," toward Earth. In space terms, we say, "down toward Earth" is the nadir direction. The opposite direction, away from Earth toward space, is the zenith direction.

Similarly, launch vehicles need to control their attitude to steer into the correct orbit and keep forces aligned along the long axis where they are strongest. However, in this section, we'll focus mainly on the unique problems for spacecraft. Because this function is so important, it is sometimes given a separate name—*attitude determination and control subsystem (ADCS)*. In this section, we'll refer to it by that name. Regardless of the name given to the subsystem, its job is the same—keep its spacecraft pointed in the right direction.

In the last section, we learned that all closed-loop control systems have the same basic components and functions, as shown in Figure 4.3.1-6. In this section, our "desired state" is the specific attitude a vehicle needs to do its mission. We start by defining this desired attitude. Then, we move on to the first function of any control system—understanding system behavior. We explore attitude dynamics to understand the basic principles that govern a vehicle's angular momentum. We also see how various phenomena in the space environment affect a spacecraft's attitude. After this introduction, we'll turn our attention to attitude sensors to learn how we use instruments to "look out the window" to determine a spacecraft's orientation in space. Before looking at attitude controllers, we'll first examine the types of attitude actuators available to designers. With these in mind, we'll finally consider the controller and see how the entire subsystem fits together (Figure 4.3.1-6).

Having the Right Attitude

Before we go too far, let's review some basic terms used to describe attitude. To describe attitude we must define a coordinate system and we're now interested in rotation rather than translation. For this reason,

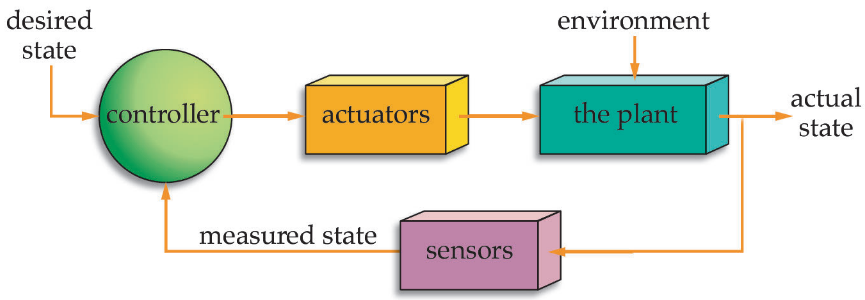


Figure 4.3.1-6. Closed-loop Control System. All closed-loop control systems have the same basic elements. The desired state is one input to the controller. It compares this state to the actual state from the sensors. By comparing the difference between these two input signals, it decides on specific commands to send to the actuators. Actuator changes, along with environmental inputs, affect the final output of the plant. System sensors detect and measure this output.

we define attitude in terms of angles instead of distances. Attitude is described as an angular rotation with respect to a body-centered coordinate frame, called the *body frame*, where $\hat{X}$ points out the nose, $\hat{Y}$ out the left wing, and $\hat{Z}$ out the top, as shown in Figure 4.3.1-7. It is usually given as roll, pitch, and yaw angles, where *roll* is a rotation about the $\hat{X}$ axis, *pitch* is a rotation about the $\hat{Y}$ axis, and *yaw* is a rotation about the $\hat{Z}$ axis, as shown in Figure 4.3.1-8. Obviously, box-shaped spacecraft don't have noses or wings. Instead, designers define preferred directions through the center of mass in a body-centered system and then they define roll, pitch, and yaw angles with respect to it.

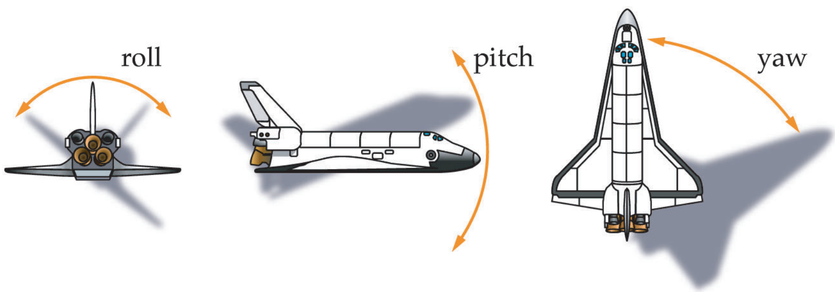


Figure 4.3.1-8. Describing Attitude. We describe space-vehicle attitude in terms of roll, pitch, and yaw angles around the axes of the body frame.

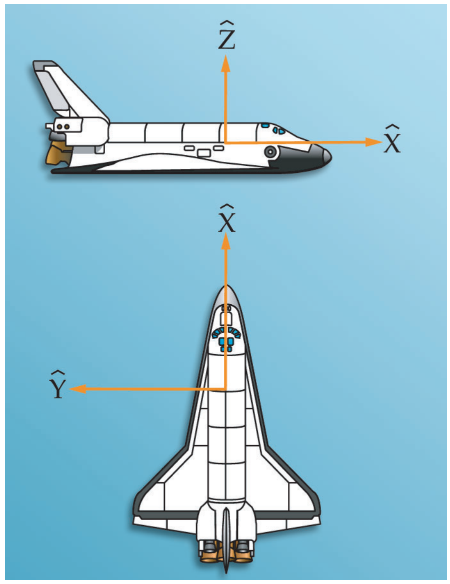


Figure 4.3.1-7. Body Frame. We describe attitude in terms of rotations in degrees (or radians) around one or more of the body-centered axes from the body frame. For airplanes and vehicles like the Space Shuttle, the $\hat{X}$-direction points out the nose, the $\hat{Y}$-direction points out the left wing, and the $\hat{Z}$-direction (out of the page) completes the right-hand rule. For box-shaped spacecraft without a "nose" or wings, designers pick convenient, preferred directions through the center of mass to define the body frame.

Now that we showed how to describe a spacecraft's attitude, how do we determine whether it has the right attitude? We must first know what attitude it needs. Typically, we describe attitude-control requirements in terms of accuracy and rate of attitude change. To understand what we mean by attitude or pointing accuracy, let's pretend we're trying to point a laser beam at a target, as shown in Figure 4.3.1-9. Our ability to keep the beam on the target depends on the size of the target and the steadiness of our hand. It should make sense that the smaller the target, the more steady our hand must be to maintain the laser on it. Hopefully, even as our hand wavers, the beam will tend to stay within a cone, more or less centered on the target. The angular size of this cone defines *pointing* or *attitude accuracy, ψ*. For a spacecraft trying to point an antenna at a ground station on Earth, for example, the control system must be accurate enough to keep the radio beam focused over the receiver antenna.

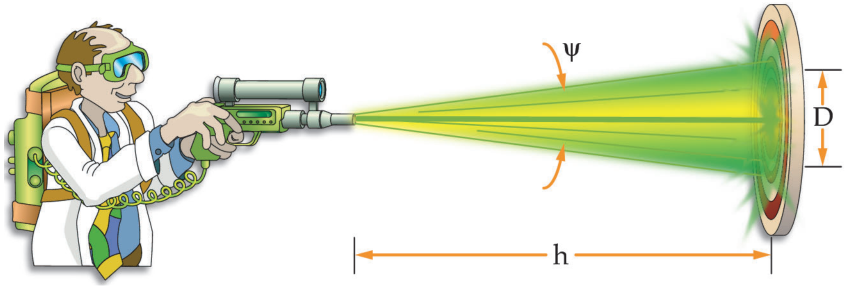


Figure 4.3.1-9. Attitude Accuracy. In this example, the shooter is pointing a laser beam at a dinner-plate-sized target. As his hand wavers, the beam describes a cone, more or less centered on the target. The angular size of this cone, ψ, defines attitude or pointing accuracy.

To get a better feel for what we mean by attitude or pointing accuracy, let's pretend the target in Figure 4.3.1-9 is about the size of a 25-cm (10-in.) dinner plate. We know the pointing accuracy, ψ, and the distance to the target, h. To find the apparent diameter of the target we can hit, D, we use

$$D = h\,\psi \qquad (4.3.1\text{-}1)$$

where

D = approximate diameter of target (m)

h = distance to target (m)

ψ = pointing accuracy (rad)

Table 4.3.1-1 shows the required pointing accuracy to stay focused on the dinner plate at various distances.

Table 4.3.1-1. Pointing Accuracy.

To point at a target the size of a dinner plate (25 cm or 10 in. diameter) at this distance...	The pointing accuracy needs to be...
1.4 m (4.6 ft.)	10°
14 m (46 ft.)	1°
140 m (460 ft.)	0.1°
1400 m (0.87 mi.)	0.01°

Now let's put this in space terms. A remote-sensing spacecraft passing directly overhead at an altitude of 500 km (310 mi.), for example, would need about 0.003° of accuracy to point a laser range finder directly at a house (D = 26 m or 85 ft.). Fortunately, pointing a laser beam is a worst-case scenario because the narrow beam has a very narrow field of view. Remote-sensing missions using optical or infrared cameras typically have lenses with fields of view of several degrees or more, depending on the application. To give the widest possible coverage, communication missions will often design antennas with very wide fields of view. The actual requirement for spacecraft pointing, then, depends on the subject, the sensor's field of view, and other factors, such as timing and viewing angles.

The rate of attitude change is also important to consider when defining attitude-control requirements. For example, a remote-sensing spacecraft may need to shift its attention between various targets on the ground. To shift attention means it must rapidly change its attitude to focus on a new point of interest. *Slew rate* is the angular speed (in degrees, or radians, per second) describing how fast the spacecraft can change its attitude.

Now that we understand more about describing attitude, let's start to see how we control it by first trying to understand attitude dynamics. We'll then turn our attention to environmental factors that affect attitude and that spacecraft must deal with.

Attitude Dynamics

As we know, all spinning objects—tops, yoyos, ice skaters, and even spacecraft—follow Newton's Laws of Motion. Recall from Chapter 4 that a spinning mass has angular momentum, which is a function of its shape, mass distribution, and rate of spin. Notice, for example, that a compact object with all the mass concentrated near the center of mass spins much easier than an object that has a lot of mass located far from the center of mass. As Figure 4.3.1-10 shows, this is why figure skaters bring their arms in to spin faster and extend their arms to slow down. The distribution of mass describes an object's *mass moment of inertia, I*. By knowing the mass moment of inertia, I, and the object's angular velocity, $\vec{\Omega}$, we can find its angular momentum, $\vec{H}$.

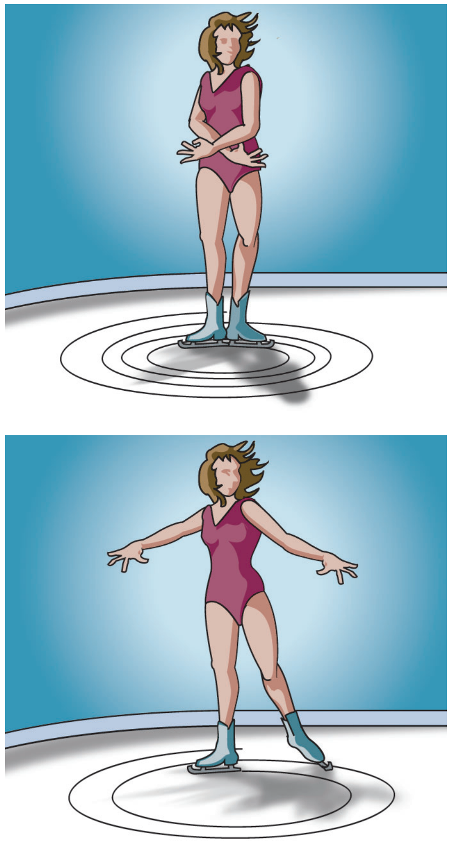


Figure 4.3.1-10. Changing Mass Moment of Inertia. Figure skaters change their moments of inertia to vary their rate of spin. For the same total angular momentum, they will spin faster by bringing their arms in (lower moment of inertia) and slower by extending their arms (higher moment of inertia).

Important Concept

An object's angular momentum, $\vec{H}$, depends on both its moment of inertia, I, and its angular velocity, $\vec{\Omega}$

This is summarized by Equation (4.3.1-2)

$$\vec{H} = I\vec{\Omega} \tag{4.3.1-2}$$

where
$\vec{H}$ = angular momentum ($kg \cdot m^2/s$)
I = mass moment of inertia ($kg \cdot m^2$)
$\vec{\Omega}$ = angular velocity (rad/s)

We also know from Section 4.1.3 that to change an object's momentum we must apply a force. When we kick a football or serve a volleyball, it's not hard to see that applying a force to a mass changes its velocity. But how do we apply force to a rotating mass? If we push on spinning ice skaters they'll start moving in a straight line across the ice while continuing to spin. What if we want to change only their rate or direction of spin but not move them anywhere? Then we must apply a torque. A *torque* is a twisting force that results when we try to rotate an object, such

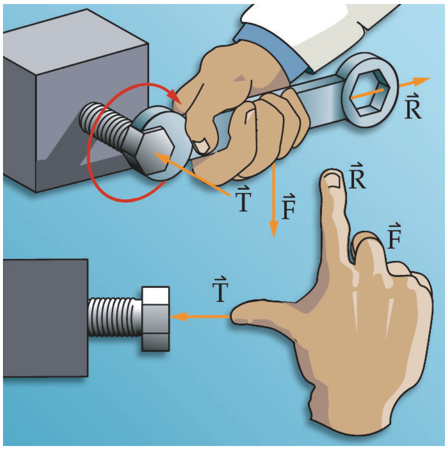


Figure 4.3.1-11. Torque. Turning a bolt with a wrench is a good example of applying a torque. You find the direction of torque using the right-hand rule. By wrapping the fingers of your right hand in the direction of spin, your thumb points in the direction of the torque vector. In this case, the torque direction is into the bolt, as we'd expect.

as when we use a wrench to turn a bolt. We apply a force some distance away from the bolt, producing a torque, as shown in Figure 4.3.1-11. A torque in one direction tightens the bolt. A torque in the other direction loosens it.

If you point the fingers of your right hand in the direction of the twist, your thumb points in the torque-vector direction. In Figure 4.3.1-11, we have a force applied to the end of a wrench. The torque vector, $\vec{T}$, points into the bolt.

Important Concept

The magnitude of an applied torque depends on the force and distance over which it is applied. The direction of torque is found using the right-hand rule.

According to this relationship, we can get more torque with the same force by simply applying the force farther from the center of rotation. Aristotle knew of this effect when he bragged he could move the Earth if given "a fulcrum, a long enough staff, and a place to stand." We don't have to move the Earth to see this effect. All we have to do is push open a door. If we push at the edge of the door, far from the hinges, the door swings right open. If we push on the door right next to the hinges, it's much harder to move.

Returning to Newton's Second Law, we can now see how to relate torque and angular momentum. Just as force equals the time rate of change of linear momentum, torque is the time rate of change of angular momentum. In other words, if we apply a torque to an object, its angular momentum will change. When torque is zero, angular momentum stays constant. Later, we'll see we can use this basic principle to give us accurate attitude sensors, as well as efficient actuators to control attitude. For now let's see how we can use it to analyze how attitude works. Remember that if we apply a force to an object, it will accelerate. Similarly, if we apply a torque to a free-floating object, it will start to spin faster and faster. That is, it will experience angular acceleration, $\vec{\alpha}$.

Important Concept

If you apply a torque, $\vec{T}$, to an object with a given mass moment of inertia, I, the object will experience angular acceleration, $\vec{\alpha}$, spinning faster and faster the longer the torque is applied.

This concept is summarized in Equation (4.3.1-3)

$$\vec{T} = I\vec{\alpha} \qquad (4.3.1\text{-}3)$$

where

I = mass moment of inertia ($kg \cdot m^2$)

$\vec{\alpha}$ = angular acceleration ($rads/s^2$)

As we know from our discussion of linear motion, as something accelerates over time, it acquires velocity. If we drop a ball, it accelerates, gains velocity, and falls faster with time. Similarly, when an object has angular acceleration over time, it gains angular velocity, $\vec{\Omega}$. Thus, to determine a spacecraft's attitude, described by an angle θ (an amount the spacecraft rotated from its previous attitude), we must look at how long it accelerates and how long it moves at some angular velocity. In other words, by applying a torque to a non-spinning, free-floating object (such as a spacecraft), we create angular acceleration, leading to angular velocity and hence a change in angular position. The model for this aspect of spacecraft behavior is the block diagram in Figure 4.3.1-12.

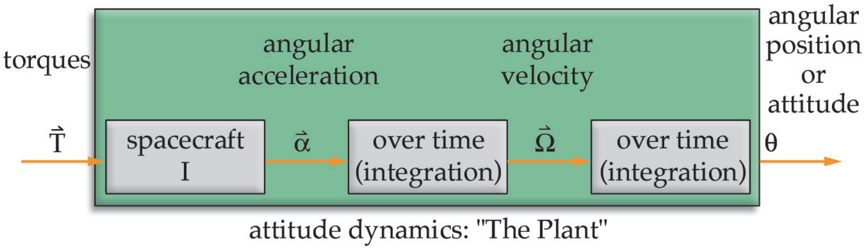


Figure 4.3.1-12. Block Diagram of Attitude Dynamics. A torque applied to a spacecraft (or any object for that matter) causes an angular acceleration. Over time, this acceleration increases angular velocity, changing its attitude.

When we apply a torque to a non-spinning spacecraft, predictable things happen. For example, when we turn a screw with a screwdriver, it rotates in the way we'd expect. But if the spacecraft is spinning when we apply the torque, the dynamics get more complicated. As we know, a spinning object has angular momentum. Applying a torque *parallel* to the angular momentum direction, causes angular acceleration and angular velocity changes. However, applying the torque in a direction other than parallel to the angular momentum vector causes something quite different to happen.

In Figure 4.3.1-13, we have a spinning disk with a force couple (torque) applied to it. You might expect the mass to begin to rotate in the same direction you're torquing it, or clockwise as you look down on it. But that's not what happens! The mass begins to rotate counter-clockwise about an axis that comes out of the page! This phenomenon is known as *precession*.

For the disk shown in Figure 4.3.1-14, the $\vec{H}$ vector will begin to move (or precess) toward the $\vec{T}$ vector (things would behave differently if it were a different shape). This precession occurs around a third vector called the *precession vector*, $\vec{\omega}$, and is at right angles to both $\vec{H}$ and $\vec{T}$. For a constant torque, the precession rate is also constant; it doesn't accelerate, as we'd expect! As we'll see, knowing how a spacecraft gains angular velocity and precesses helps us determine how to apply forces to adjust its attitude. Note that the direction of precession depends on *how* mass is distributed in the object—its mass moment of inertia. Analyzing *why* it precesses the way it does is beyond the scope of this book.

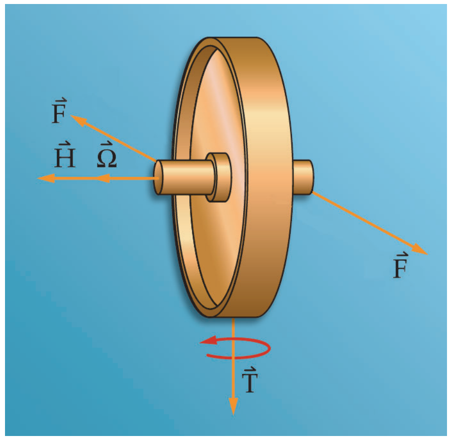


Figure 4.3.1-13. Torque Applied to a Spinning Disk. Here, the angular momentum vector, $\vec{H}$, points to the left. As we apply a force couple to the spinning disk, into and out of the page, it creates a torque, $\vec{T}$, that points down.

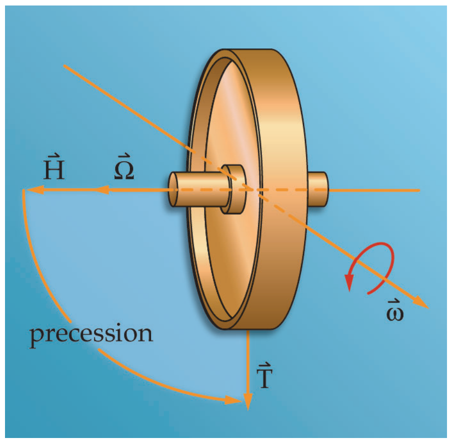


Figure 4.3.1-14. Precession of a Spinning Disk. When we apply a torque to the spinning disk, it begins to precess by rotating around an axis 90° from both the torque and angular-momentum axes. In general, $\vec{H}$ tends to move toward $\vec{T}$. Using the right-hand rule, curling your fingers from $\vec{H}$ to $\vec{T}$ allows you to predict the direction of the precession axis with your thumb.

There is one more important result of the interaction between a spinning spacecraft and an applied torque. We all know that spinning footballs and spinning rifle bullets travel farther and faster than non-spinning ones. This is because spin makes them more stable and resistant to outside torques. The faster they spin, the more stable they become. This stability is referred to as an object's *gyroscopic stiffness*. The mathematical explanation for what makes a spinning object "stiffer" than a non-spinning object is beyond the scope of our discussion here. However, as we'll see, we can use this fact to keep spacecraft pointed where we want them.

Disturbance Torques

So why can't we just stick a satellite out in space with the desired attitude and forget about it? As we know from Section 4.1.2, space can be a nasty place. Over time, if we do nothing, environmental effects called *disturbance torques* will drive a spacecraft away from its original attitude. These torques are extremely small (in most cases, they literally couldn't kill a fly). But just as tiny drops of water can wear away mountains over time, these torques can eventually rotate even very large spacecraft. We're concerned with four main sources of disturbance torques

- Gravity gradient
- Solar-radiation pressure
- Earth's magnetic field
- Atmospheric drag

We'll go through each of these before turning our attention to the problem of attitude determination.

Gravity-gradient Torque

Gravity-gradient torque results from the difference in gravitational force exerted on different parts of a spacecraft. Remember that Newton said the force of gravity on an object varies inversely with the square of the distance from the central body.

$$\vec{F}_g = \frac{-\mu\, m}{R^2}\hat{R} \qquad (4.3.1\text{-}4)$$

where
$\vec{F}_g$ = force of gravity (N)
μ = gravitational parameter of the central body (km^3/s^2)
m = mass of the object (kg)
R = distance from the object to the central body (km)
$\hat{R}$ = unit vector in the $\vec{R}$ direction (dimensionless)

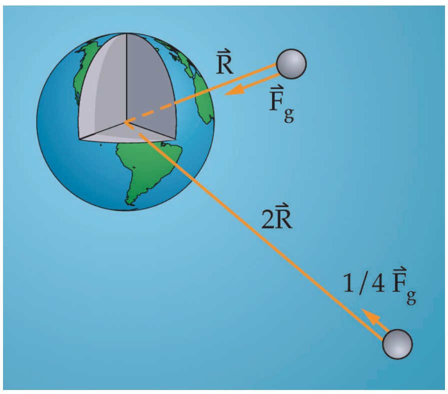


Figure 4.3.1-15. Gravitational Force. From Newton's Law of Universal Gravitation, we know that gravitational attraction decreases with the square of the distance between two objects. Thus, if we double the distance, the gravitational force is only 1/4 as strong.

Thus, as we show in Figure 4.3.1-15, if one object is twice as far from Earth as a second object, the gravitational force will be one-fourth as large. This is easy to visualize if the difference in distances from the central body is very great, but it works the same way for very small differences. Imagine we have a dumbbell-shaped spacecraft in Earth orbit. If the dumbbell is hanging vertically, as in Figure 4.3.1-16, the lower mass (m_1) will have a slightly greater gravitational force on it than the higher mass (m_2).

If m_2 is directly above m_1, nothing interesting happens. However, if the dumbbell gets displaced off vertical, as in Figure 4.3.1-17, the slight difference between the gravitational forces on the two masses will create a torque on the spacecraft that will tend to restore it to vertical. This is fine if you want it to be vertical, but if you don't, your control system must continually fight against this torque. We can estimate the magnitude of this torque using

$$T_g = \left(\frac{3\mu}{2R^3}\right)|I_Z - I_Y| \sin(2\theta) \tag{4.3.1-5}$$

where

T_g = gravity-gradient torque (Nm)

μ = gravitational constant (km^3/s^2) = $3.986 \times 10^5\ km^3/s^2$ for Earth

I_Z = spacecraft moment of inertia about the $\hat{Z}$ axis (where we assume $I_X = I_Y$ and $I_Z >> I_X$) ($kg\ m^2$)

I_Y = spacecraft moment of inertia about the $\hat{Y}$ axis ($kg\ m^2$)

θ = angle between the body $\hat{Z}$ axis and the local vertical

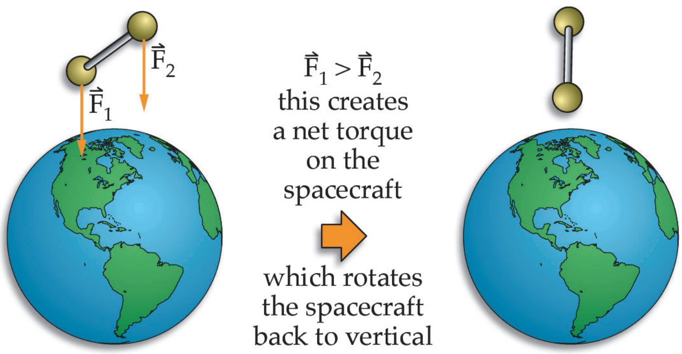


Figure 4.3.1-17. Gravity-gradient Torque. The slight difference in gravitational force between the upper and lower part of a spacecraft will tend to rotate the spacecraft to vertical, with its long axis pointed to Earth.

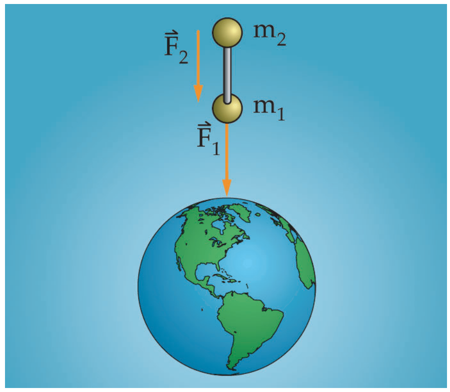


Figure 4.3.1-16. Gravity Gradient. In this simplified, dumbbell-shaped spacecraft, we show that the gravitational force on the lower part is slightly greater than the force on the upper part, $\vec{F}_1 > \vec{F}_2$. The same effect happens in more conventionally shaped spacecraft due to differences in internal mass distribution.

This equation tells us three important things about the gravity-gradient effect

- It decreases with the cube of the distance—for example, by going from a 500-km-altitude orbit (R = 6878 km) to a 1000-km-altitude orbit (R = 7378 km) the torque reduces by almost 20%
- It depends on the difference between moments of inertia in the $\hat{Z}$ axis and $\hat{X} - \hat{Y}$ plane; thus, for a homogenous spacecraft with $I_x = I_y = I_z$ the effect is zero

- It depends on the angle between the $\hat{Z}$ axis and local vertical—the greater the angle from local vertical, the greater the torque

Later in this section we'll see how we can turn this sometimes annoying effect to our advantage.

Solar-radiation Pressure

Another source of disturbance torque for spacecraft comes from the Sun. The Sun exerts an ever-so-slight force called *solar-radiation pressure* on exposed surfaces. We're used to being warmed by the Sun, tanned by the Sun, and even burned by the Sun, but pushed by the Sun? Yes. One way to think about sunlight (or any light for that matter) is as tiny bundles of energy called *photons*. In one of those seeming paradoxes of modern physics, we say these photons are massless (thus, they can travel at the speed of light), but they do have momentum. As photons strike any exposed surface, they transfer this momentum to the surface. Why can't we feel this force when we hold our hand up to the Sun? Because this force is very, very small. We can estimate the force using

$$F = \left(\frac{Fs}{c}\right) A_s (1 + r) \cos I \qquad (4.3.1\text{-}6)$$

where

F = force on a surface (N)

Fs = solar constant = 1358 W/m^2 at Earth's orbit around the Sun

c = speed of light = 3×10^8 m/s

A_s = illuminated surface area (m^2)

r = surface reflectance (where r = 1 for a perfect reflector and 0 for a perfect absorber) (unitless)

I = incidence angle to the Sun (deg)

The force exerted on even a very large spacecraft with ten square meters of surface (assuming perfect reflectance) is only 9×10^{-5} N (2×10^{-5} lb_f)! We assume this force acts at the center of pressure for the surface. The moment arm is the distance from the center of pressure to the spacecraft's center of mass. We find the resulting torque by multiplying this force times the moment arm ($T = F \times d$). Even with a 1 m moment arm, the resulting solar pressure torque is only 9×10^{-5} Nm. So why worry about it? Over time, even this tiny force, acting unevenly over different parts of the spacecraft, especially large areas like solar panels, can cause problems for spacecraft needing precise pointing. In Section 4.2.1 we saw how we harnessed this small force to propel large solar sails.

Magnetic Torque

A third source of disturbance torque comes from Earth's magnetic field. As we learned in Section 4.1.2, because of the impact of charged particles in space, the surface of a spacecraft can develop a charge of its own giving it a distinct *dipole*—north/south ends, like a compass. Just as a compass needle rotates to align with Earth's magnetic field, the dipole-charged spacecraft will similarly try to rotate as it passes through the magnetic field. The size of this *magnetic torque* depends on the spacecraft's effective magnetic dipole and the local strength of Earth's magnetic field. We estimate this from

$$T = D\,B \qquad (4.3.1\text{-}7)$$

where

T = torque on a spacecraft (Nm)

D = spacecraft dipole (amp-m^2)

B = local magnetic field's strength (tesla), which varies with altitude (R = distance to Earth's center) and latitude. Earth's magnetic moment, M, is about 7.99×10^{15} tesla-m^3. At the poles, $B = 2M/R^3$. At the equator, $B = M/R^3$. (tesla = kg/amp-s^2)

Magnetic torque is a big concern for operators of small satellites in low, polar orbit but hardly noticeable for large spacecraft in geostationary orbit. Later, we'll see how we can create a large dipole on purpose to use this torque as an attitude actuator.

Aerodynamic Drag

The last disturbance torque we have to worry about is drag. As we saw in Section 4.1.2, in low-Earth orbit the atmosphere applies a drag force to a vehicle, eventually causing it to re-enter the atmosphere and burn up. In Section 4.1.7 we introduced the drag force as

$$F_{drag} = \frac{1}{2}\,\rho\,V^2\,C_D\,A \qquad (4.3.1\text{-}8)$$

where

F_{drag}= force of drag (N)

ρ = atmospheric density (kg/m^3)

V = velocity (m/s)

C_D= drag coefficient (unitless)

A = impacted area (m^2)

Because parts of a spacecraft may have different drag coefficients (solar panels, for example, act like big sails), drag forces on different parts of the spacecraft can also differ. This difference, along with the distance between the center of pressure (where the drag acts) and the center of mass, causes a *drag torque*. A spacecraft designer can do little to prevent this torque (short of moving the spacecraft to a higher orbit), so again the control system must be designed to deal with it.

Spacecraft Attitude Sensors

As we've seen, an essential element of closed-loop control systems is a device that can watch what's happening to the system and report this information to the controller. In other words, we need a sensor. Sensors are the control system's "eyes and ears." Sensors observe the system to determine attitude and transform these observations into signals that the controller processes.

All of us have a built-in attitude-sensor system. As we know from our discussion of the human vestibular system in Section 4.1.2, we use fluid flowing over tiny hairs in our inner ear, along with information from our eyes, to detect changes in our attitude. For example, they sense if we're standing up or falling over. If we suddenly tilt our head to the side, these sensors detect this motion. If our body violently moves or shakes (such as when we ride a roller coaster), our eyes and inner ear can get "out of synch," leading to motion sickness. Fortunately, spacecraft don't get sick from all their rotating, but they do need good attitude sensors. So let's look at a spacecraft's eyes and ears.

To understand how sensors help spacecraft determine their attitude, pretend you're flying the Space Shuttle in low-Earth orbit and need to point the nose at some spot on the surface. You're in the commander's seat facing toward the nose. To point the nose at the surface, you must first determine where you're pointed now. How can you do this? The obvious answer is to look out the window at some reference. Let's say you see the Sun out the left-hand window. Would this tell you all you need to know? Unfortunately, no. A single reference point gives your current attitude in only two dimensions. In other words, you'd know that the left wing is pointed at the Sun and the nose is pointed perpendicular to the Sun. But the nose could point in various directions and still be perpendicular to the Sun, so what do you do?

To determine your attitude in three dimensions, you need another reference. If you could see some known star out the front window you'd know your orientation with respect to two reference points—the Sun and a star. Knowing the angle between the Sun and the Earth and between a known star and Earth, you could determine how to change your attitude to point the nose at Earth. Let's look at how we can apply this technique for attitude determination.

"Looking out the Window"

When pilots fly along in their airplanes, the easiest way for them to determine attitude is to look out the window (if the weather is good). If the ground is down and the sky is up, they're flying upright. Similarly, the simplest way for a spacecraft to determine its attitude is to just "look out the window." One important class of attitude sensors works the same way as remote-sensing payloads (on some spacecraft, the payload can actually serve both functions). Recall, to look at a subject, a remote-sensing system must

- Look at it—scan the sensor to point at the subject
- See it—collect EM radiation from it
- Convert it—transform EM radiation into a usable data

- Process it—turn data into usable information

When it comes to remote sensing for attitude determination, three main subjects are available for reference—Earth, the Sun, and the Stars. This gives us three classes of "out-the-window" sensors

- Earth sensors
- Sun sensors
- Star sensors

All these sensors work in pretty much the same way as other remote-sensing devices. Typically, they are attached to the spacecraft so the spacecraft must rotate to bring the subject into the sensor's field of view or rely on "targets of opportunity" that will routinely go in and out of the field of view. Similar to a telescope or camera, EM radiation from the primary subject enters through a lens and focuses on solid state detectors, such as the charged-coupled devices. The sensor's accuracy depends on how precisely it can discriminate the target, or portion of the target, and how much onboard processing it can accomplish.

In low-Earth orbit, Earth fills a big portion of the sky. *Earth sensors* can roughly indicate the "down" direction by simply discriminating where Earth is with respect to the rest of the sensor's field of view. At geostationary altitude, the angular radius of Earth is about 10°, so a sensor that can find Earth is at least accurate to within that amount. To use Earth as a more accurate method of attitude determination, a sensor must focus only on one small part. Conveniently, sensors can detect Earth's horizon by focusing on a narrow band of EM radiation emitted by carbon dioxide, CO_2, in the atmosphere, as shown in Figure 4.3.1-18. These Earth-horizon sensors can be as much as ten times more accurate than a simple Earth detector.

Sun sensors, the most widely used for spacecraft attitude, are similar in function to Earth sensors. As the name implies, a Sun sensor finds the Sun and determines its direction with respect to the spacecraft-body frame, as shown in Figure 4.3.1-19. By their nature, Earth and Sun sensors can give accurate information about attitude in only two dimensions. For example, this means an Earth or Sun sensor can measure pitch and roll relative to the horizon, but not yaw; or pitch and yaw but not roll, etc.

A more accurate 2-axis reference is a *star sensor*. As Figure 4.3.1-20 shows, star sensors measure a spacecraft's attitude with respect to known star locations. Then they compare these measurements to accurate maps of the brightest stars stored in the spacecraft's memory. The angle between the known star's position and a reference axis on the spacecraft, θ, then helps determine the spacecraft's inertial attitude. By using two or more star sensors located around a spacecraft (or by taking multiple measurements with the same sensor), the system can determine its attitude in three dimensions.

As we mentioned, each of these sensors provides only a 2-D reference. To determine attitude in three dimensions, we often use two or more sensors together. For example, onboard computers can combine data

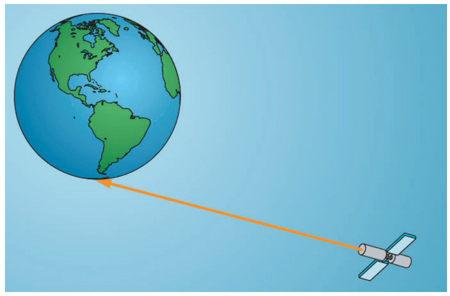


Figure 4.3.1-18. Earth Sensors. As their name implies, Earth sensors use Earth as a target for determining spacecraft attitude. Sensors focus either on the gross direction of Earth or on narrower (and more accurate) parts of Earth, such as the horizon.

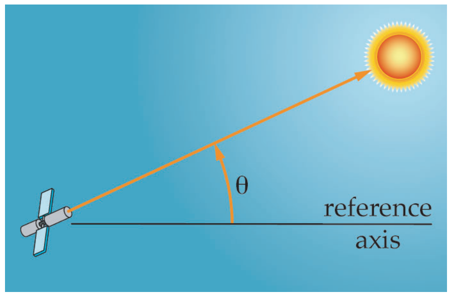


Figure 4.3.1-19. Sun Sensor. A Sun sensor determines spacecraft attitude by finding the direction of the Sun with respect to the body frame. Like Earth sensors, this sensor can only give a 2-dimensional fix on attitude without another point of reference.

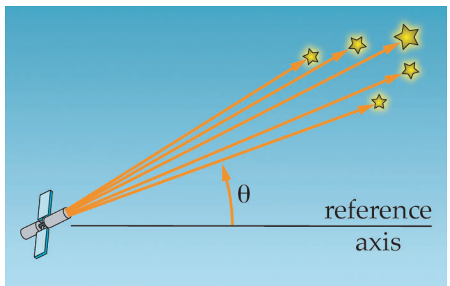


Figure 4.3.1-20. Star Sensor. A star sensor determines a spacecraft's attitude with respect to the known orientation of certain, bright stars.

from an Earth sensor with Sun-sensor data to get a 3-D, accurate fix. As we'll see, all of these sensors can also work with a spacecraft's "ears"—gyroscopes and magnetometers.

Gyroscopes

Gyroscopes, like our inner ear, can determine attitude and changes in attitude, directly, without needing to look out the window. The simplest type of gyroscope is a spinning mass. As we know, any spinning mass has angular momentum that is conserved. By using this basic principle, we can use the gyroscope to detect a spacecraft's angular motion. Two basic principles of gyros make them useful as attitude sensors

- With no torques, their angular momentum is conserved—they always point in the same direction in inertial space
- With torque applied, they precess in a predictable direction and amount

When a mass starts to spin, its angular-momentum vector remains stationary in inertial space, unless acted on by an outside torque. For example, let's spin a gyroscope at 6:00 A.M. (see Figure 4.3.1-21) with its angular-momentum vector pointed at some convenient inertial reference—say, a star just above the eastern horizon (somewhere to the right side of the page). We can then observe how conservation of angular momentum works to keep the gyro always pointed in the same inertial direction, as long as no torque affects it.

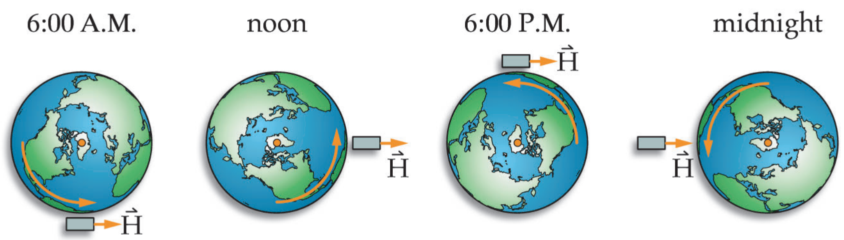


Figure 4.3.1-21. Conservation of Angular Momentum. A spinning mass, such as a gyroscope, has angular momentum that is naturally conserved. If we spin a freely rotating gyro pointing east at 6 A.M., in this polar view of Earth, it appears to rotate as the day goes on. Actually, the Earth-bound observer rotates with Earth, but the gyro stays pointing in the same direction in inertial space.

In this case, the angular-momentum vector, $\vec{H}$, appears to "track" the star because the star is essentially fixed in inertial space. As the gyro sits in its stand, it looks like it's rotating throughout the day. Actually, the stand is moving as Earth rotates. The gyro remains stationary in inertial space. Museums often demonstrate this principle with huge pendulums suspended on long cables. The swinging pendulum's plane remains fixed in inertial space, but as Earth turns, the pendulum's path appears to move, knocking over dominos spaced around it to the delight of the crowds.

The second basic principle of gyroscopes relates to their strange motion in response to an applied torque. Earlier, we called this motion precession—rotation with constant angular velocity in a direction 90° from the direction of the applied torque.

Knowing these two basic principles, let's see how we can use a gyro to sense attitude. Because its angular momentum vector stays constant in inertial space, it provides a constant reference for inertial direction. One way to measure rotation with respect to the reference is to isolate the gyro from torques by mounting it on a *gimbal* (hinged brackets that allow it to rotate freely or that allow the mounting box to rotate freely around the stationary gyro). We then mount the gimbal on a platform in a spacecraft and measure the spacecraft's rotation by measuring how much the spacecraft rotates with respect to the stationary gyro.

Another way to measure a spacecraft's rotation is to strap a gyro directly to the spacecraft. Then, when the gyro (or the spacecraft) rotates around an axis perpendicular to the spin vector, the resulting torque will cause the gyro to precess. By measuring this precession angle and rate, the system can compute the amount and direction of the spacecraft's rotation and thus determine its new attitude.

Newer types of gyroscopes, called *ring-laser gyroscopes*, don't use these principles of a spinning mass. They use principles associated with laser light! A ring-laser gyro consists of a circular cavity containing a closed path, through which two laser beams shine in opposite directions (it's all done with mirrors). As the vehicle rotates, the path lengths traveled by the two beams change, causing a slight change in the frequency of both beams. By measuring this frequency shift, the system can compute the vehicle's rate of rotation. By integrating this rate over time, it can determine the amount of rotation and hence the vehicle's new orientation. Ring-laser technology offers similar or better accuracy, with greater reliability than the old style spinning-mass gyros.

Magnetometers

Another means of measuring attitude directly uses Earth's magnetic field. A *magnetometer* is basically a fancy compass that measures the direction of the magnetic field and its strength. Earlier, when we discussed the disturbance torque caused by the magnetic field, we indicated its strength varies with the cube of radius (R^3) and by a factor of two between the pole and equator. By comparing the measured direction and strength of the local field with a high fidelity model of Earth's field, the sensor can determine the orientation of the spacecraft with respect to Earth. An engineering drawing of a magnetometer is shown in Figure 4.3.1-22.

To see how this works, think about a compass needle. It's usually just a lightweight magnet that can rotate freely. If you've ever played with magnets, you know that one side of a magnet will readily attract and stick to another magnet, while the opposite side will repel it. With magnets, opposites attract and likes repel, so the north pole of a magnet attracts the south pole of another magnet. The lightweight magnet rotating freely in a compass tries to do the same thing. The north end of the compass tends to point at Earth's North Pole, and suddenly, you're no longer lost!

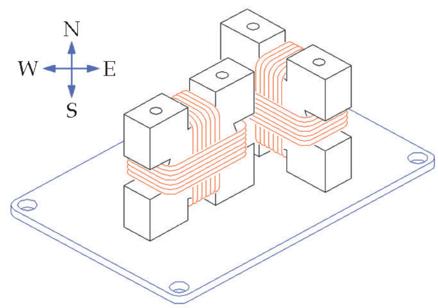


Figure 4.3.1-22. Magnetometers. A magneto-meter functions as a highly accurate compass that measures the direction and strength of the local magnetic field. By comparing this measurement to a model of Earth's field, it can determine an accurate estimate of the current attitude. *(Courtesy of Maarten Meerman, Surrey Satellite Technology, Ltd.,*

Use of magnetometers is limited by the strength of the field, making them more useful in low-Earth orbit than at geostationary altitude. The sensor accuracy depends on the accuracy of the field model. Even so, they offer a relatively inexpensive sensor that can deliver an independent reference from the other sensors we've discussed.

Global Positioning System (GPS)

The newest attitude sensor to emerge on the scene is the "differential" *Global Positioning System (GPS)*. GPS is a constellation of 24 satellites in high Earth orbit (12-hour period) designed and deployed by the U.S. Air Force to provide world-wide position, velocity, and time information. Clever engineers figured that by placing two GPS receivers some distance apart on a vehicle, and carefully measuring the difference between the two signals, they could determine a vehicle's attitude. This attitude-determination technique may offer a relatively inexpensive, independent system for spacecraft in low-Earth orbits.

Spacecraft Attitude Actuators

After we've determined what our spacecraft's attitude is, we need to know how to change it. For example, we may need to compensate for disturbance torques or rotate the spacecraft to point at a new subject. As we've seen, applying a torque changes a vehicle's attitude. That's why we need actuators. Actuators provide "torque on demand" to rotate a spacecraft as needed to take pictures, downlink data, or meet other mission requirements.

Many types of attitude actuators are available to spacecraft designers. Just as several different types of sensors often work together to accurately measure attitude, typically two or more types of actuators combine to apply torque to achieve a desired attitude. For simplicity, we'll discuss each type of actuator separately.

We can conceptually divide actuator types into two general classes, passive and active. *Passive actuators* operate more or less open loop. In other words, after the spacecraft is in the desired attitude, passive actuators will keep it there with little or no additional torques needed. *Active actuators*, on the other hand, require continuous feedback and adjustment. As you would expect, passive actuators typically can't reach the same level of accuracy as active ones; however, in many cases, they're good enough. We'll look at three types of passive actuators

- Gravity-gradient stabilization
- Spin stabilization
- Dampers

and three types of active actuators

- Thrusters
- Magnetic torquers
- Momentum-control devices

Gravity-gradient Stabilization

The first type of passive actuator takes advantage of the gravity-gradient disturbance torque discussed earlier. We can exploit this “free” torque to keep a spacecraft oriented in a local vertical, or “downward,” orientation. Fortunately, a spacecraft doesn’t have to be shaped like a dumbbell to take advantage of this effect. For example, why do we see only one face of the Moon and never the mysterious “dark side?” Because of uneven distribution of mass within the Moon’s crust, it’s in a gravity-gradient-stabilized attitude with respect to Earth. However, to maximize the effect of this cheap and reliable attitude actuator, spacecraft will usually deploy weighted booms to create a more dumbbell-like shape. Figure 4.3.1-23 shows an artist’s conception of the PicoSAT spacecraft using a 6 m deployable boom.

Gravity-gradient attitude control offers a simple, reliable, inexhaustible (as long as there’s gravity) system with no moving parts. However, it has a few drawbacks

- Control of only two axes—pitch and roll but not yaw
- Limited accuracy—depending on the spacecraft’s moments of inertia, downward pointing accuracy is only about ±10°
- Only effective in low-Earth orbit—because gravity varies with the square of the distance, it’s not very effective beyond LEO

Despite these disadvantages, gravity-gradient-controlled spacecraft have been used effectively on a variety of missions.

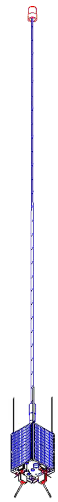


Figure 4.3.1-23. Gravity-gradient Stabilization. Some spacecraft take advantage of the gravity-gradient torque to keep them oriented in a local vertical, or “downward,” attitude. Usually, they maximize this effect by deploying a small mass at the end of a very long boom. This artist’s conception of the PicoSAT spacecraft shows it to scale with a 6-m-long deployable boom and a small mass on the end. *(Courtesy of Surrey Satellite Technology, Ltd., U.K.)*

Spin Stabilization

Earlier we saw that a spinning mass has unique gyroscopic properties. A *spin-stabilized* spacecraft takes advantage of the conservation of angular momentum to maintain a constant inertial orientation of one of its axes. Because the angular-momentum vector, $\vec{H}$, of a spinning mass is fixed in inertial space, the spacecraft tends to stay in the same inertial attitude, as shown in Figure 4.3.1-24.

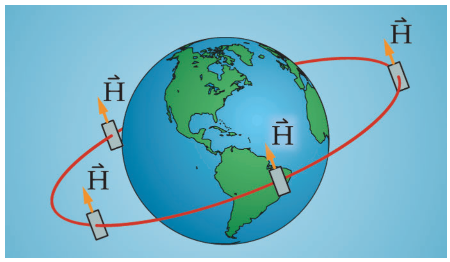


Figure 4.3.1-24. Spin Stabilization. A spinning spacecraft keeps its angular-momentum vector fixed in inertial space.

Perhaps the best example of a spin-stabilized satellite is Earth. The spinning Earth is essentially a giant gyroscope. Earth’s $\vec{H}$ vector points out of the North Pole. This $\vec{H}$ stays fixed in inertial space (except for a minor wobble), always pointed at the same place in the sky. When we observe the motion of the stars at night, we see they all appear to rotate around one star—the North Star. This occurs because Earth’s $\vec{H}$ vector points at the North Star!

Spin stabilization is useful, as long as we want our spacecraft to stay pointed in the same inertial direction. However, usually we’re more interested in non-inertial pointing. For example, spin stabilization isn’t very useful for pointing $\vec{H}$ at Earth, as illustrated in Figure 4.3.1-25. For this reason, we mostly use it only during spacecraft deployment, when the natural gyroscopic stiffness we discussed earlier is useful to maintain a known orientation until the spacecraft is free from the launch vehicle. This spin is usually maintained through the first major maneuver,

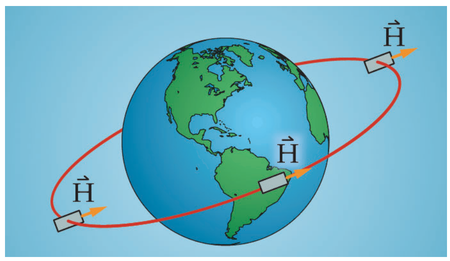


Figure 4.3.1-25. Spin Stabilization Isn’t Much Good for Earth Pointing. Because spin stabilized spacecraft have fixed pointing with respect to inertial space, they aren’t a good choice for Earth-pointing missions. During part of the orbit, they may point toward Earth but during other parts of the orbit, they’ll point away.

providing a stiff, stable platform during a rocket firing. During high-thrust, orbit-insertion rocket firings, spin stabilization is often the only technique that can efficiently keep the spacecraft stable.

One way to avoid Earth-pointing limitations of spin stabilization is to use a dual-spin system. *Dual-spin systems* also take advantage of the constant angular momentum vector of a spinning mass. These systems consist of an inner cylinder called the "de-spun" section, surrounded by an outer cylinder that is spinning at a high rate. The outer cylinder provides overall spacecraft stability. The word "de-spun" is actually a misnomer. In fact, the "de-spun" section does spin, but at a much slower rate than the outer section. To allow for antenna and sensor pointing, the "de-spun" section spins at a rate to keep them pointed at Earth. For example, if a spacecraft is in geostationary orbit, the de-spun section rotates at "orbit rate" or once every 24 hours, keeping antennas or other sensors focused on Earth, as shown in Figure 4.3.1-26.

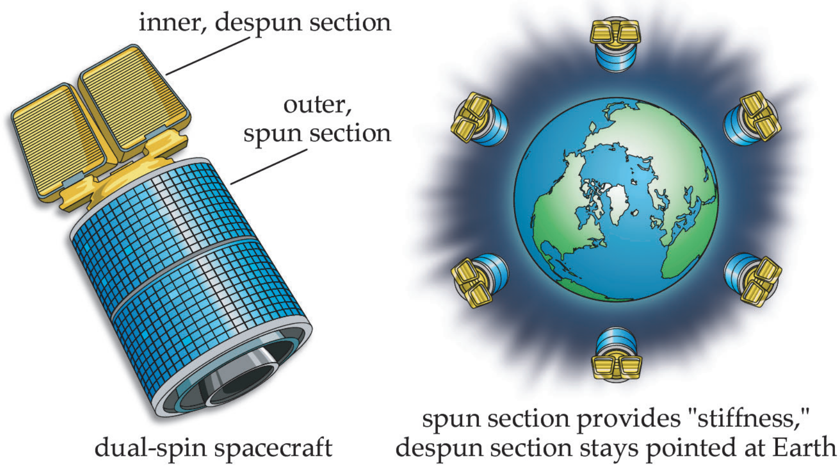


Figure 4.3.1-26. Dual-spin Spacecraft. A dual-spin spacecraft uses the inherent stiffness of a spinning outer section with a "de-spun" inner section that can independently point at Earth. The de-spun section turns at the orbital rate to keep sensors and antenna pointed at Earth.

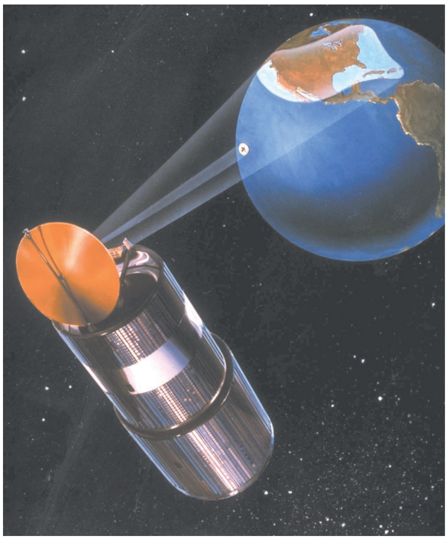


Figure 4.3.1-27. Dual-spin Communication Spacecraft. Large geosynchronous communication spacecraft, such as the Satellite Business Systems spacecraft, shown here, make good use of dual-spin attitude control. *(Courtesy of Hughes Space and Communications Company)*

Of course, the need for independently spinning sections makes dual-spin spacecraft much more complex. Electrical and other connections must run from the spun to the "de-spun" sections. Highly reliable bearings must allow the two sections to spin at different rates with little friction. Even with these inherent technical challenges, dual-spin has been a popular control option for large, geosynchronous, communication spacecraft, such as the one shown in Figure 4.3.1-27.

Dampers

As mentioned earlier, we seldom use a single type of attitude actuator alone. A damper is another actuator usually used in combination with others for a complete system. Generally speaking, a *damper* is a device that changes angular momentum by absorbing energy. We know momentum is constant only as long as energy stays constant. If we add or take away energy, momentum changes. As a spacecraft attitude actuator, dampers absorb unwanted momentum. Where does it go? When we hit the brakes in a car, the linear momentum "goes" into heat produced by friction between the brake pads and the disks or drums. Similarly, attitude dampers use friction or other means to convert angular-momentum energy into other forms.

One simple type of momentum damper consists of a small ball in a circular tube filled with highly viscous fluid, as illustrated in Figure 4.3.1-28. As a spacecraft rotates, some of its momentum is contained in the ball that moves inside the tube. Friction between the ball and the fluid in the tube converts some of the momentum into heat that slowly dissipates throughout the spacecraft. Over time, the spacecraft can use this simple technique to absorb mechanical energy, slowing it's rotation. Dampers are usually designed and oriented to reduce rotation about a specific axis. In this way, designers often use them in spinning spacecraft to remove unwanted "wobbles" in the spin axis.

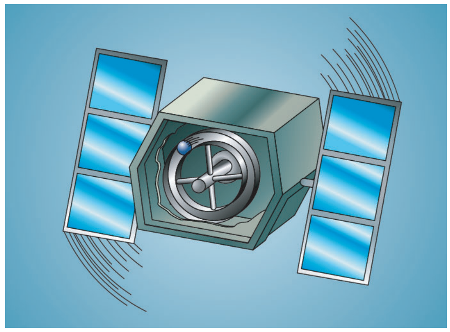


Figure 4.3.1-28. A Simple Spacecraft Damper. Dampers "absorb" unwanted angular momentum by converting the energy into friction, in much the same way as the brakes in a car turn linear momentum into heat through friction. A ball inside a circular tube filled with a viscous fluid is one type of damper. As the spacecraft rotates, the ball moves through the fluid. The resistance produces heat, dissipating the angular motion.

Thrusters

All of the actuators we've discussed so far are passive, in that, once put in motion, they can more or less function in an open-loop mode, with little or no additional inputs. Now we'll turn our attention to active actuators. Thrusters are perhaps the simplest type of active actuator to visualize. *Thrusters* are simply rockets that rely on "brute force" to rotate a spacecraft. By applying a balanced force with a pair of rockets on opposite sides of a spacecraft, we can produce a torque, as shown in Figure 4.3.1-29. By varying which thruster pair we use and how much force we apply, we can rotate a spacecraft in any direction.

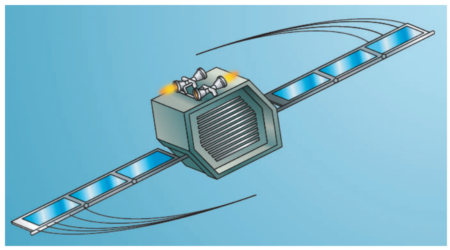


Figure 4.3.1-29. Thrusters. Thrusters are rockets that apply a force some distance away from the center of mass, causing a torque that rotates the spacecraft.

Placing thrusters as far from the satellite's center of mass as possible gives them a larger moment arm and allows them to exert a greater torque for a given force. This is evident from the important concept we saw earlier. The greater the distance over which a force is applied, the more torque is delivered from the same force. However, as we learned earlier, because of precession, when a spacecraft is already spinning, any applied torque in a direction other than the spin axis causes the spacecraft to rotate at constant velocity about an axis perpendicular to the torque direction.

The biggest advantage of using thrusters is that they can produce a well defined "torque on demand," allowing the spacecraft to slew quickly from one attitude to another. Unfortunately, the amount of propellant a spacecraft can carry limits their use. For short missions, such as those flown by the Space Shuttle, this limit is no problem. For longer missions (months or years), designers use thrusters only as a backup and for other purposes we'll discuss later. We'll explore basic principles of rocket science and propulsion system technologies in greater detail in Section 4.2.1.

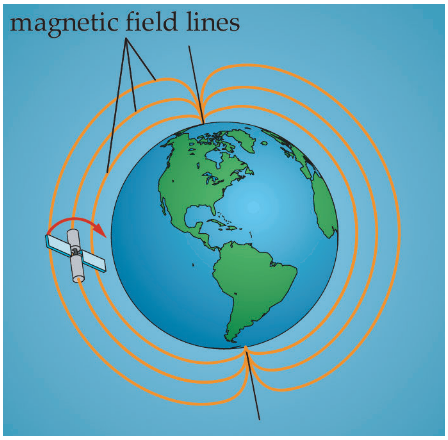


Figure 4.3.1-30. Magnetic Torquers. A magnetic torquer is an active spacecraft-attitude actuator that takes advantage of the natural torque caused by Earth's magnetic field interacting with a magnet; it's the same effect that rotates a compass needle. Onboard, the system switches electromagnets on and off as needed, pushing "against" the magnetic field and producing the necessary torque.

Magnetic Torquers

A *magnetic torquer* is another type of actuator that takes advantage of a naturally occurring torque in the space environment. Earlier we looked at the magnetic disturbance torque caused by the interaction of the spacecraft's magnetic field due to surface charging with Earth's magnetic field. We can use this effect in an active mode by creating powerful onboard magnets and switching them on and off as needed to rotate "against" Earth's magnetic field. Magnetic torquers are simply electromagnets produced by running an electrical current through a loop of wire onboard. Like a compass needle, this electromagnet tries to align with Earth's magnetic field, dragging the rest of the spacecraft with it, as seen in Figure 4.3.1-30.

Magnetic torquers offer a relatively cheap and simple way to control a spacecraft's attitude. Furthermore, because they need only electrical power to run, they're inexhaustible—unlike thrusters. Unfortunately, their effectiveness depends directly on the strength of Earth's magnetic field, so they become less useful in higher orbits. Also, because the field strength varies by a factor of two between the equator and the poles, they are most useful in highly inclined orbits. Even so, they are an important secondary means of attitude control used on many LEO spacecraft.

Momentum-control Devices

The most common actuator for spacecraft attitude control is a family of systems that all rely on angular momentum. These *momentum-control devices* actively vary the angular momentum of small, rotating masses within a spacecraft to change its attitude. How can this work? If you stand on a turntable, holding a spinning bicycle wheel at arm's length, you can cause yourself to rotate by tilting the bicycle wheel to the left or right. This works because total angular momentum of a system is always conserved. As the bicycle wheel rotates one way, you rotate another to compensate, keeping the total angular momentum constant, as you can see in Figure 4.3.1-31.

Let's look at where this attitude change comes from. From Equation (4.3.1-2), we know angular momentum is the product of an object's mass moment of inertia, I, and its angular velocity, $\vec{\Omega}$.

$$\vec{H} = I\vec{\Omega} \quad (4.3.1\text{-}2)$$

Note that a large mass (high I) spinning at a relatively slow speed (low $\vec{\Omega}$) can have exactly the same angular momentum as a small mass (low I) spinning at a much higher rate (high $\vec{\Omega}$). If we consider a spacecraft and all mass inside it to be one system, we can control where the spacecraft points by changing the angular momentum (rate and direction of spin) of a small spinning mass inside. Three approaches to momentum-control devices are in wide use

- Biased momentum systems—"Momentum wheels" that typically rely on a single wheel with a large, fixed momentum to provide

Figure 4.3.1-31. Bicycle Wheels in Space? You can do a simple experiment to see one way spacecraft control their attitude. By standing on a turntable and holding a spinning bicycle wheel, as shown in the left-hand photograph, you can change direction (your attitude). You'd simply apply a small torque to the wheel by slightly tilting the wheel to one side, as shown in the right-hand photograph.

overall stiffness. The wheel's speed gradually increases to absorb disturbance torques.

- Zero-bias systems—"Reaction wheels" that rely on three or more wheels, normally with little or no initial momentum. Each wheel spins independently to rotate the spacecraft and absorb disturbance torques.
- Control-moment gyroscopes— rely on three or more wheels, each with a large, fixed momentum. The wheels are mounted on gimbals, rotating the wheels about their gimbals changes the spacecraft orientation.

Biased momentum systems are the simplest type of momentum control device. In operation, these systems use one or two continually spinning *momentum wheels*, each with a large, fixed momentum. (They are "biased" toward having a particular, set momentum, hence the name). Because they are always spinning, they give the spacecraft a large angular-momentum vector, fixed in inertial space. This is exactly the same concept used by spin-stabilized spacecraft, discussed earlier. Only, in this case, instead of spinning the whole spacecraft, we only spin a small wheel inside the spacecraft to achieve the same effect, as illustrated in Figure 4.3.1-32.

In contrast, *reaction wheels* are a type of *zero-bias system*, because their normal momentum is at or near zero (no bias). Typically, an attitude control system uses at least three separate reaction wheels, oriented at right angles to each other, as seen in Figure 4.3.1-33. Often, a fourth wheel

Figure 4.3.1-32. Biased Momentum Systems. We use momentum wheels in biased momentum systems. They typically rely on a single wheel with a large, fixed ("biased") momentum to provide overall stiffness. The wheel speed gradually increases to absorb disturbance torques. *(Courtesy of Ball Aerospace & Technologies Corporation)*

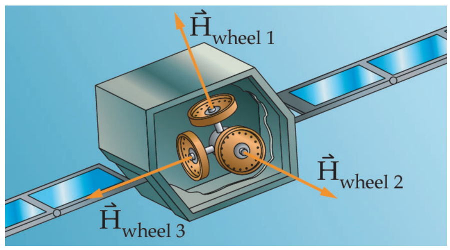


Figure 4.3.1-33. Reaction Wheels. Reaction wheels are part of a zero-bias system that uses three independent wheels, one along each axis, normally with zero or nearly zero momentum. To rotate the spacecraft or absorb disturbance torques, one or more wheels begin to spin. Often, designers add a fourth wheel, skewed with respect to the other three, for redundancy.

is skewed to the other three for redundancy. When the spacecraft needs to rotate to a new attitude, or to absorb a disturbance torque, the system spins one or more of these wheels. To see how this works, let's step through what happens to the relationship between a reaction wheel and the overall spacecraft momentum.

First of all, recognize that without any external torque, the total angular momentum of the spacecraft (including the reaction wheels) is conserved (and usually maintained at or near zero). Thus, the angular momentum of the spacecraft plus the angular momentum of the reaction wheels must add to a constant vector quantity. Now, imagine one of the reaction wheels begins to spin using a motor. As the wheel's spin rate increases, its angular momentum also increases. But the total angular momentum of the wheel and spacecraft must always sum to a constant value. So what happens to the spacecraft?

Let's look at a more specific example to get a better idea. We can express the total angular momentum of the spacecraft (including reaction wheels) as

$$\vec{H}_{TOT} = \vec{H}_{S/C} + \vec{H}_{RW} \qquad (4.3.1\text{-}9)$$

where

$\vec{H}_{TOT}$ = total angular momentum of the spacecraft (kg m^2/s)

$\vec{H}_{S/C}$ = angular momentum of just the spacecraft (kg m^2/s)

$\vec{H}_{RW}$ = angular momentum of the reaction wheels (kg m^2/s)

[*Note:* This relationship is vector addition, so $|\vec{H}_{TOT}| \neq |\vec{H}_{S/C}| + |\vec{H}_{RW}|$!]

If a reaction wheel spins faster, its angular momentum increases by an amount $\Delta\vec{H}_{RW}$. Because the total angular momentum must stay constant, the spacecraft's angular momentum *must* automatically decrease to compensate by an amount $\Delta\vec{H}_{S/C}$. The vector increase in the reaction wheel's momentum must exactly equal the decrease in the spacecraft's momentum, or $\Delta\vec{H}_{RW} = -\Delta\vec{H}_{S/C}$, to keep a constant total. Figure 4.3.1-34 shows these relationships. To conserve momentum, the spacecraft must either slow its rotation or start rotating in the opposite direction. In either case, the spacecraft's attitude has changed simply by spinning a small mass faster inside.

Figure 4.3.1-35. Reaction Wheels for Accurate Pointing. The Hubble Space Telescope observes many interstellar objects at such long distances that it must point very accurately. To be this accurate, it relies on very accurate reaction wheels. *(Courtesy of NASA/Johnson Space Center)*

Three reaction wheels can deliver precise control of a spacecraft's attitude in all three axes. Unfortunately, as with any mechanism with moving parts, they can be complex, expensive, and have a limited operational lifetime. Despite these limitations, they remain the primary choice for attitude control on large, modern spacecraft requiring very accurate pointing, such as the Hubble Space Telescope shown in Figure 4.3.1-35.

The final type of momentum-control device is the *control-moment gyroscope (CMG)*. A CMG consists of one or more spinning wheels, each mounted on gimbals that allow them to rotate freely in all directions. Recall that reaction wheels change momentum by changing magnitude only (spinning faster or slower). CMGs change momentum by changing their magnitude *and* direction (physically rotating the spinning wheel).

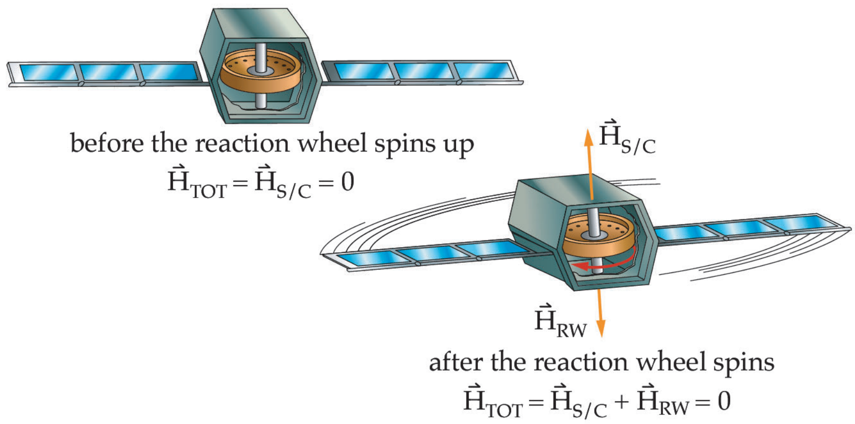


Figure 4.3.1-34. Reaction Wheels in Operation. The total angular momentum of a spacecraft system is the sum of the spacecraft's momentum plus the momentum of each reaction wheel. In this example, we start with a non-rotating spacecraft that has zero total angular momentum. To rotate the spacecraft in one direction, a reaction wheel is spun up in the opposite direction, such that the total angular momentum of the system stays constant.

Again, because the total angular momentum of the system must be conserved, as the momentum of a CMG changes in one way, the spacecraft will rotate in the other to compensate. CMGs provide pointing accuracy equivalent to reaction wheels but offer much higher slew rates and are especially effective on very large platforms, such as the Skylab Space Station shown in Figure 4.3.1-36.

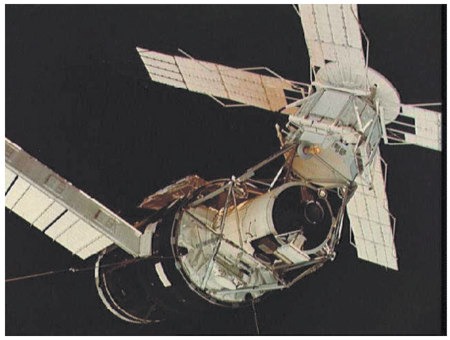


Figure 4.3.1-36. A Control Moment Gyroscope (CMG) in Space. CMGs can vary the magnitude and direction of their angular momentum, allowing for much higher slew rates and making possible efficient attitude control on very large platforms, such as the Skylab Space Station shown here. *(Courtesy of NASA/Johnson Space Center)*

One important limitation of all momentum control devices is the practical limit on how fast a given wheel can spin. In operation, all of these systems must gradually spin faster and faster to rotate the spacecraft and absorb disturbance torques. Eventually, a wheel will be spinning as fast as it can, without damaging bearings or other mechanisms. At this point, the wheel is "saturated," meaning it has reached its design limit for rotational speed. When this happens, the wheels must "de-saturate" through a process known as "momentum dumping." *Momentum dumping* is a technique for decreasing the angular momentum of a wheel by applying a controlled torque to the spacecraft. The wheel can absorb this torque in a way that allows it to reduce its rate of spin. Of course, this means the spacecraft needs some independent means of applying an external torque. For this reason, on all spacecraft using momentum control devices, designers use either magnetic torquers or thrusters (or both) to allow for momentum dumping.

The Controller

So far, we've looked at the dynamics of rotating systems to understand how torque affects a spacecraft's angular momentum, including the environmental sources for disturbance torques. We then looked at the various types of sensors used to measure attitude. Finally, we discussed the different types of actuators, passive and active, used to generate torques that allow us to freely change a spacecraft's attitude. Now we can put the entire attitude determination and control subsystem together by looking at the "brains" of the operation—the controller.

The controller's job is to generate commands for the actuators to make the spacecraft point in the right direction based on mission requirements for accuracy and slew rate. To use the information from sensors and continuously adjust actuator commands, the controller must be smart. It has to know what's happening and decide what to do next. To do this right, the controller has to keep track of

- What's happening now
- What may happen in the future
- What happened in the past

Knowing what's happening now is pretty easy—the controller simply asks the sensors to find the current attitude. It then compares this to the desired attitude. The difference between the measured and desired attitude is the *error signal*. Based on this error signal, the controller steers in the direction of the proper orientation. That is, if the attitude is 10° off, the controller commands a 10° change. This is known as *proportional control* and is used in some form in virtually all closed-loop control systems.

However, predicting what's going to happen and remembering what's happened in the past can be just as important. For example, if you need to stop at a stop sign, you need to know not only where you are, but also how fast you're going, so you can hit the brakes in time. Similarly, to hit the desired attitude, the spacecraft controller must monitor the attitude rate, as well as the current attitude. For you calculus buffs, you may recognize this rate of change calculation as a derivative. In this case, by knowing the rate of change or "speed" of attitude, the controller can more accurately determine how to command the actuators to achieve better accuracy. This process is called *derivative control*.

Sometimes we can be more precise by keeping track of how close we're getting to the desired result. One way to do this is for the controller to monitor the angular difference between the measured and desired attitude, $\Delta\theta$. When the spacecraft reaches the desired attitude, this difference, $\Delta\theta$, will be zero. If the system stops commanding the actuators at this point, the attitude will immediately begin to drift due to disturbance torques. A really smart controller, however, won't just look at the instantaneous $\Delta\theta$. Instead, it would keep a running tally, summing the $\Delta\theta$ over time. The result would always be some value other than zero and would tell the controller how much torque to add in a "steady-state" mode to compensate for the disturbance torques. In calculus, this process is called integration, so we call this type of control *integral control*. Designers use it for highly accurate pointing.

Regardless of the exact scheme used, the controller combines its memory with its current measurements and an ability to predict future behavior to decide how to command the actuators. We can now complete a block diagram of a spacecraft's attitude-control system in Figure 4.3.1-37.

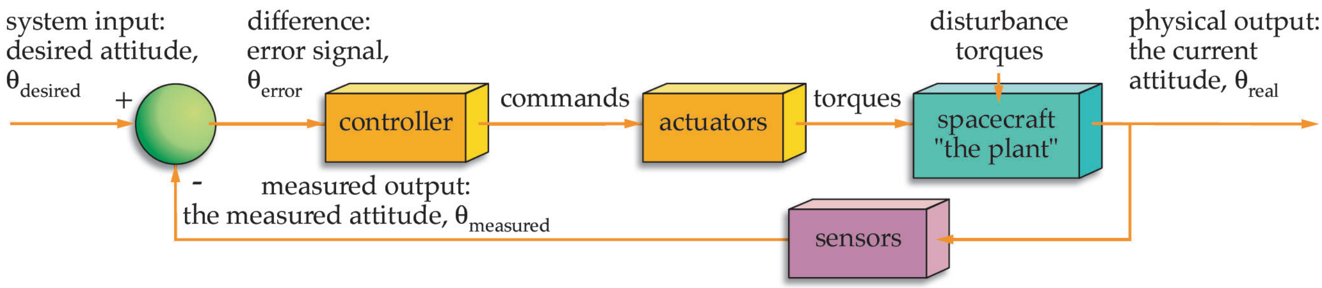


Figure 4.3.1-37. Attitude Determination and Control Subsystem (ADCS). A complete ADCS (the attitude part of an AOCS) includes a controller, actuators, the spacecraft ("the plant"), and sensors that work together to maintain or change spacecraft attitude in response to changing mission requirements.

Section Review

Key Concepts

➤ To understand a spacecraft's behavior or how it reacts to inputs, we must understand the model of system dynamics based on linear and rotational laws of motion. To rotate a spacecraft we must recognize that

- Angular momentum is always conserved
- A torque describes the direction of a force couple applied to a system
- A torque applied to a non-spinning object (or applied parallel to the direction of spin for a spinning object) causes angular acceleration, which leads to angular velocity and hence, change in angular orientation
- A torque applied in a direction other than the direction of spin for a spinning object will cause precession. This means it will begin to rotate at constant angular velocity about an axis perpendicular to the torque direction.

➤ A Spacecraft experiences many environmental disturbance torques that, over time, work to change its attitude. These include

- Gravity gradient
- Magnetic
- Solar-radiation pressure
- Atmospheric drag

➤ Sensors determine a spacecraft's attitude

- Sun sensors, horizon sensors, and star sensors are the "eyes" of the spacecraft, determining attitude by "looking out the window." They work in much the same way as remote-sensing payloads.
- Gyroscopes are the "inner ears" of spacecraft. They can directly sense changes in attitude because a spinning mass has two important properties

  –The angular momentum of a spinning mass is constant

  –Torque applied to a spinning mass causes precession
- Ring-laser gyros measure the changing frequency of light to detect attitude changes

Continued on next page

Section Review (Continued)

Key Concepts (Continued)

- Magnetometers measure the direction and magnitude of Earth's magnetic field to determine attitude
- Differential Global Positioning System (GPS) measures the difference between signals received at two or more locations on a spacecraft to determine attitude

➤ Applying torques to the spacecraft requires spacecraft actuators. Actuators are either passive or active.

➤ Passive attitude actuators include
- Gravity-gradient stabilization
- Spin stabilization
- Dampers

➤ Active attitude actuators include
- Thrusters
- Magnetic torquers
- Momentum-control devices
  –Zero-bias systems—momentum wheels
  –Bias momentum systems—reaction wheels
  –Control moment gyros

➤ The controller decides what commands to send to active actuators based on current and historical data from sensors and an understanding of spacecraft rotational properties

References

Asimov, Isaac. *Asimov's Biographical Encyclopedia of Science and Technology.* Garden City, NJ: Doubleday and Company, Inc., 1972.

Chetty, P.R.K. *Satellite Power Systems: Energy Conversion, Energy Storage, and Electronic Power Processing.* George Washington University Short Course 1507. October, 1991.

Chetty, P.R.K. *Satellite Technology and Its Applications.* THB Professional and Reference Books, New York, NY: McGraw-Hill, Inc., 1991.

Gere, James M., Stephen P. Timoshenko. *Mechanics of Materials*. Boston, MA: PWS Publishers, 1984.

Gonick, Larry and Art Huffman. *The Cartoon Guide to Physics.* New York, NY: Harper Perennial, 1991.

Gordon, J.E. *Structures: Why Things Don't Fall Down*. New York, NY: Da Capp Press, Inc., 1978.

Holman, J.P. *Thermodynamics*. New York, NY: McGraw-Hill Book Co., 1980.

Pitts, Donald R. and Leighton E. Sissom. *Heat Transfer.* Schaum's Outline Series. New York, NY: McGraw-Hill, Inc., 1977.

Wertz, James R. and Wiley J. Larson. *Space Mission Analysis and Design.* Third edition. Dordrecht, Netherlands: Kluwer Academic Publishers, 1999.

Wertz, James R. [ed.] *Spacecraft Attitude Determination and Control.* Netherlands: D. Reidel Publishing Co., Kluwer

Example 12-1

Problem Statement

Based on your experience in designing the FireSat payload, you've now been put in charge of the attitude-control system. For the FireSat constellation to provide continuous coverage, the center of the sensor's FOV must not deviate from nadir by more than ±100 km. Determine the corresponding attitude accuracy required. Given this accuracy, complete a conceptual design of the FireSat's attitude-control subsystem using the simplest available techniques. Draw a simple block diagram for your resulting subsystem.

Problem Summary

Given: D = 100 km
h = 500 km (from Example 11-1)
Find: ψ, conceptual design of FireSat attitude control system

Conceptual Solution

1) Determine ψ, for the given D and h, using Equation (4.3.1-1)

$$D = h\psi$$

$$\psi = \frac{D}{h}$$

2) Complete a conceptual design of the FireSat's attitude-control system using the simplest techniques.

3) Draw a simple block diagram for the subsystem.

Analytical Solution

1) Determine ψ, given D and h

$$\psi = \frac{D}{h} = \frac{100 \text{ km}}{500 \text{ km}}$$

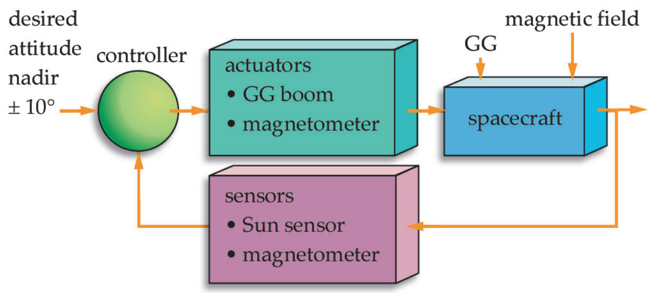
$$\psi = 0.2 \text{ rad}$$

$$\psi = 11.459°$$

2) Complete a conceptual design of the FireSat's attitude-control system, using the simplest techniques.

We could use almost an infinite number of possible control schemes to achieve modest pointing accuracy. Given that the spacecraft will operate in LEO and must be mainly nadir pointing, the simplest technique would be gravity-gradient stabilization. The addition of a short boom (2 m–3 m) with a small mass at the tip (~1 kg) should provide enough gravity-gradient torque to keep the spacecraft nadir pointing. To ensure the payload is pointing "right side down," a small magnetorquer could also be added. Three-axis attitude determination can be done using a simple sun sensor (2-axis) plus a magnetometer (3-axis).

3) Draw a simple block diagram for the subsystem.



Interpreting the Results

Given the computed attitude accuracy and the conceptual design of the FireSat's attitude-control system, we can present the system block diagram, as shown above. As team players in the overall spacecraft design, we need to consider the corresponding requirements this particular subsystem will have on other spacecraft subsystems. For example, using a gravity-gradient boom will mean the structures and mechanisms must be able to accommodate its storage during launch and successful deployment on orbit. Using a magnetorquer will place more demands on the electrical power subsystem.