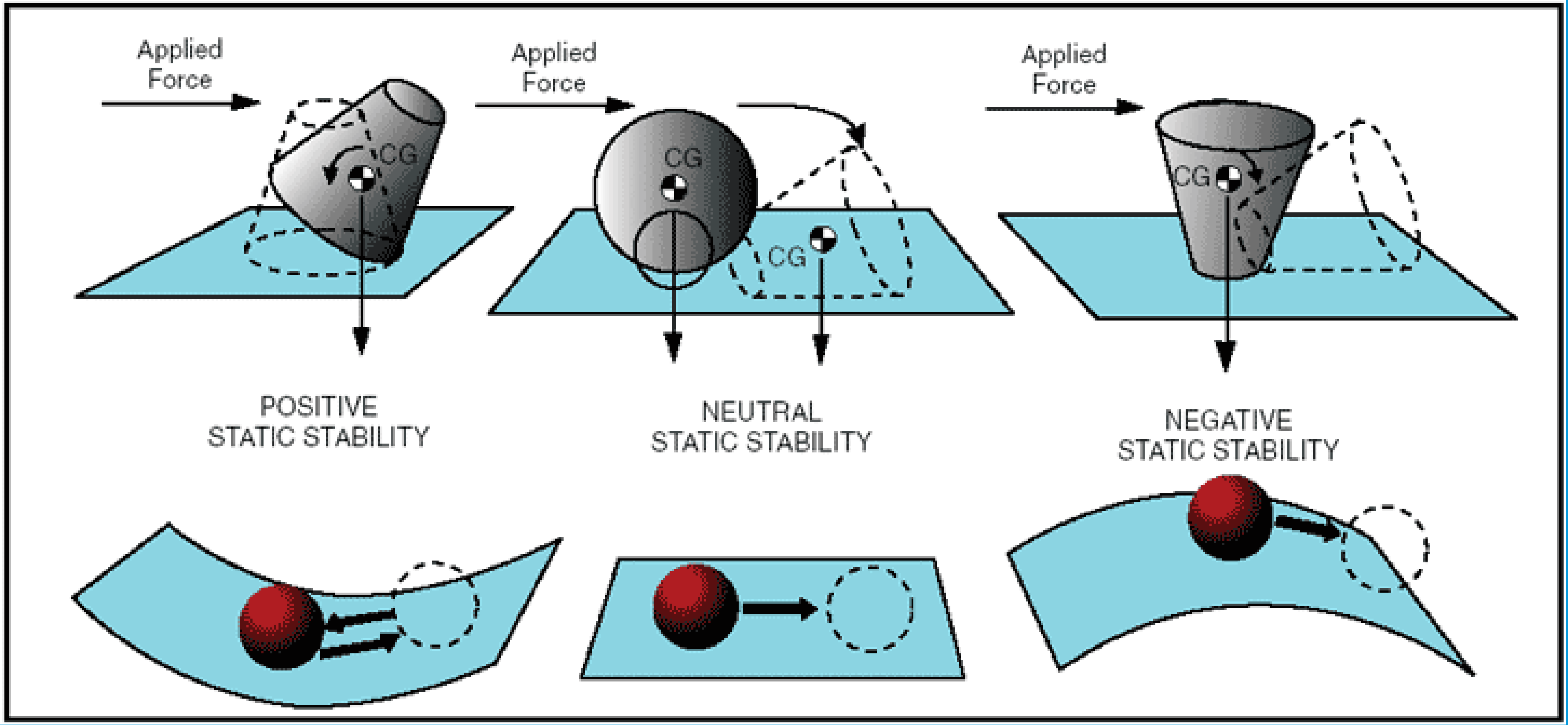
STABILITY AND CONTROL

M-3

OVERVIEW

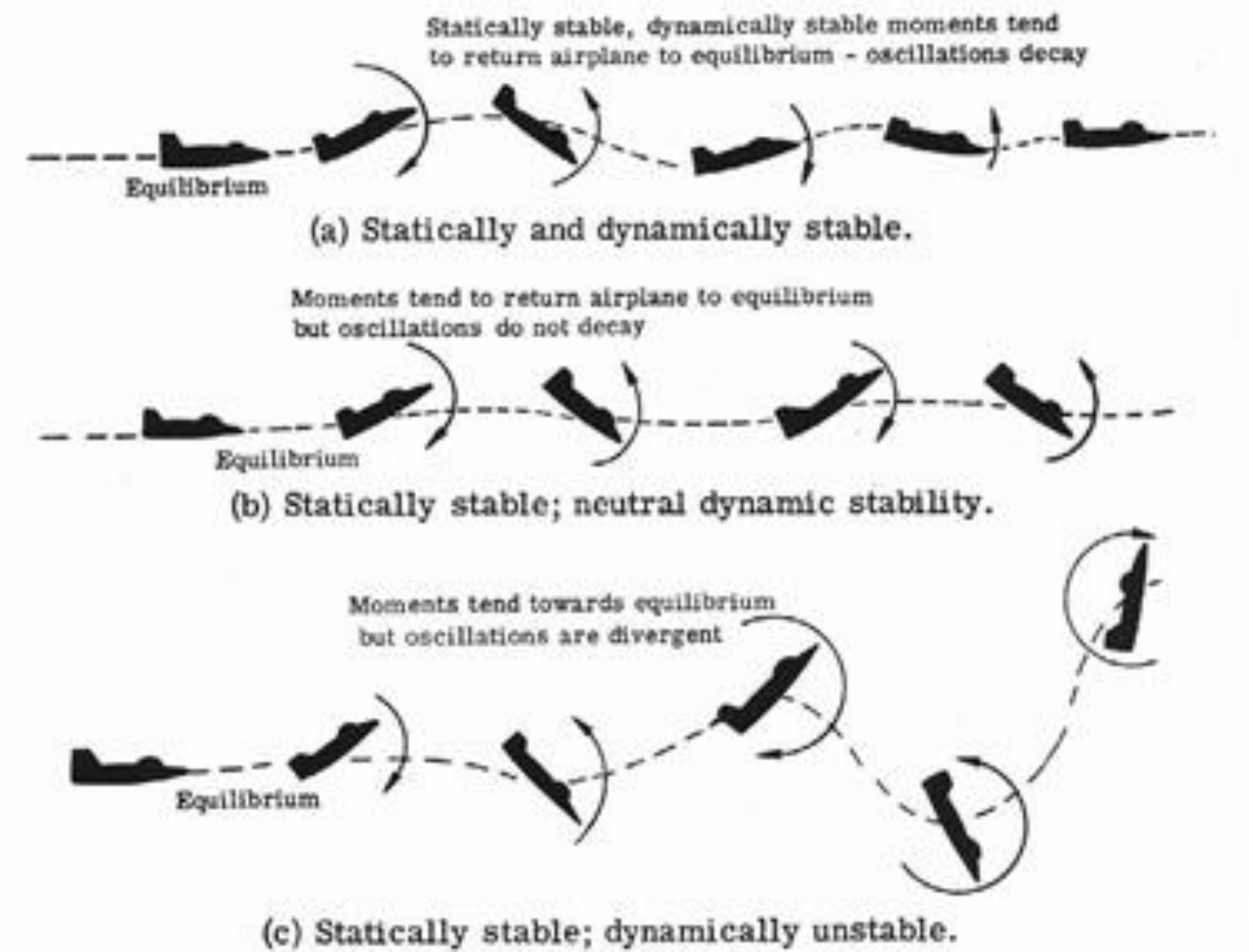
- Stability refers to the tendency of an object to remain in its present state of rest or motion despite small disturbances.



STABILITY

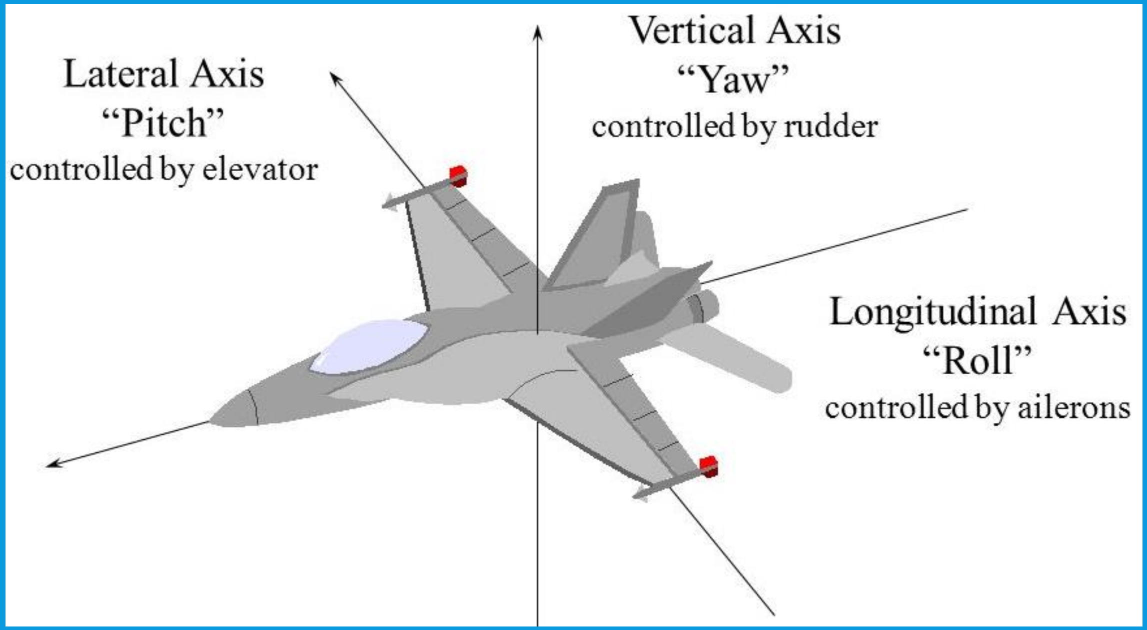
- An air vehicle must be stable if it is to remain in flight.
- Static stability implies that the forces acting on the airplane (thrust, weight, and aerodynamic forces) are in directions that tend to restore the airframe to its original equilibrium position after it has been disturbed by a wind gust or other force.
- If the air vehicle is not statically stable, the smallest disturbance will cause ever-increasing deviations from the original flight state.
- A statically stable airplane will have the "tendency" to return to its original position after a disturbance but it may overshoot, turn around, go in the opposite direction, overshoot again, and eventually oscillate to destruction. In this case, the airplane would be statically stable but dynamically unstable.
- If the oscillations are damped and eventually die out, then the air vehicle is said to be dynamically stable.

STABILITY


Statically stable, dynamically stable moments tend to return airplane to equilibrium - oscillations decay
Equilibrium
(a) Statically and dynamically stable.
Moments tend to return airplane to equilibrium but oscillations do not decay
Equilibrium
(b) Statically stable; neutral dynamic stability.
Moments tend towards equilibrium but oscillations are divergent
Equilibrium
(c) Statically stable; dynamically unstable.

STABILITY

- An air vehicle has three angular degrees of freedom (pitch, roll, and yaw) and equilibrium about each axis must be maintained.
- The pitch axis is most critical, and stability about it is called longitudinal stability.
- Some instability can be tolerated about the roll and yaw axis, which are combined in most analysis and called lateral stability.



LONGITUDINAL STABILITY

- The factors that affect longitudinal stability can be determined by referring to Figure 5.1 that shows the balance of forces on the air vehicle and Equation (3.7), which is repeated below for the reader's convenience.

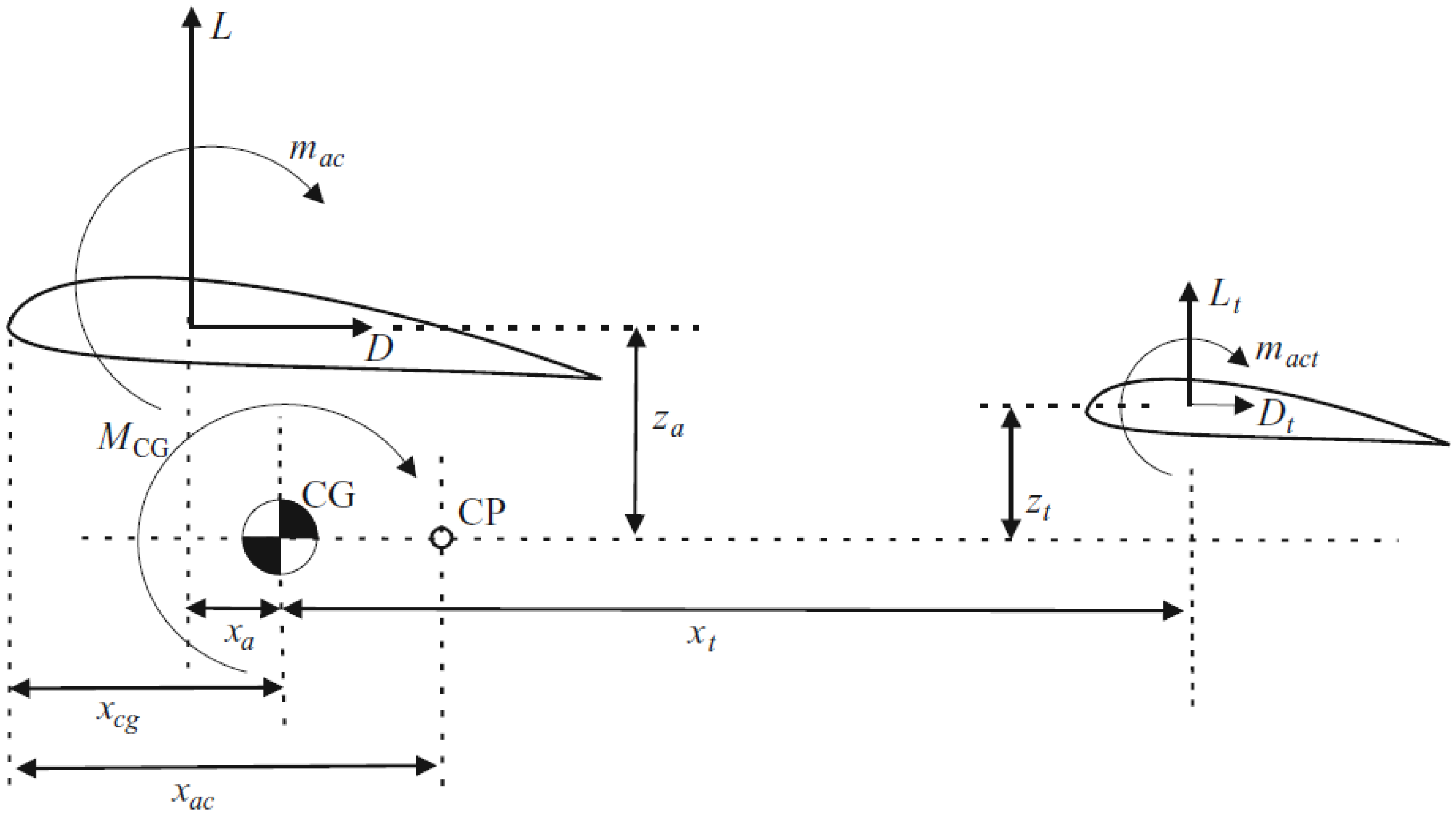


Figure 5.1 Longitudinal stability moments

$$C_{M_{CG}} = C_L\left(\frac{x_a}{c}\right) + C_D\left(\frac{z_a}{c}\right) + C_{m_{ac}} + C_{fus} - C_{L_t}\left(\frac{S_t}{S}\right)\left(\frac{x_t}{c}\right) + C_{m_{act}}$$

LONGITUDINAL STABILITY

- Using this plot, one can reason as follows: if a disturbance (e.g., increasing *CL*) causes the nose to rise and the restoring moment causes the nose to fall (e.g., the change in pitching moment is negative), the air vehicle will tend to restore itself to its original position.
- If the pitching moment causes the nose to rise further after a nose-up disturbance, then the airplane will continue to pitch up and is statically unstable.
- Mathematically, a stable system must have a pitching moment versus lift-coefficient curve with a negative slope as shown above.
- The contribution of the horizontal tail (the next to the last term in the equation) is of major importance because of its minus sign and the large value that can be obtained by designing in a large *xt* and *St*.
- A large tail area located a long distance aft of the air-vehicle center of gravity is a powerful stabilizer.

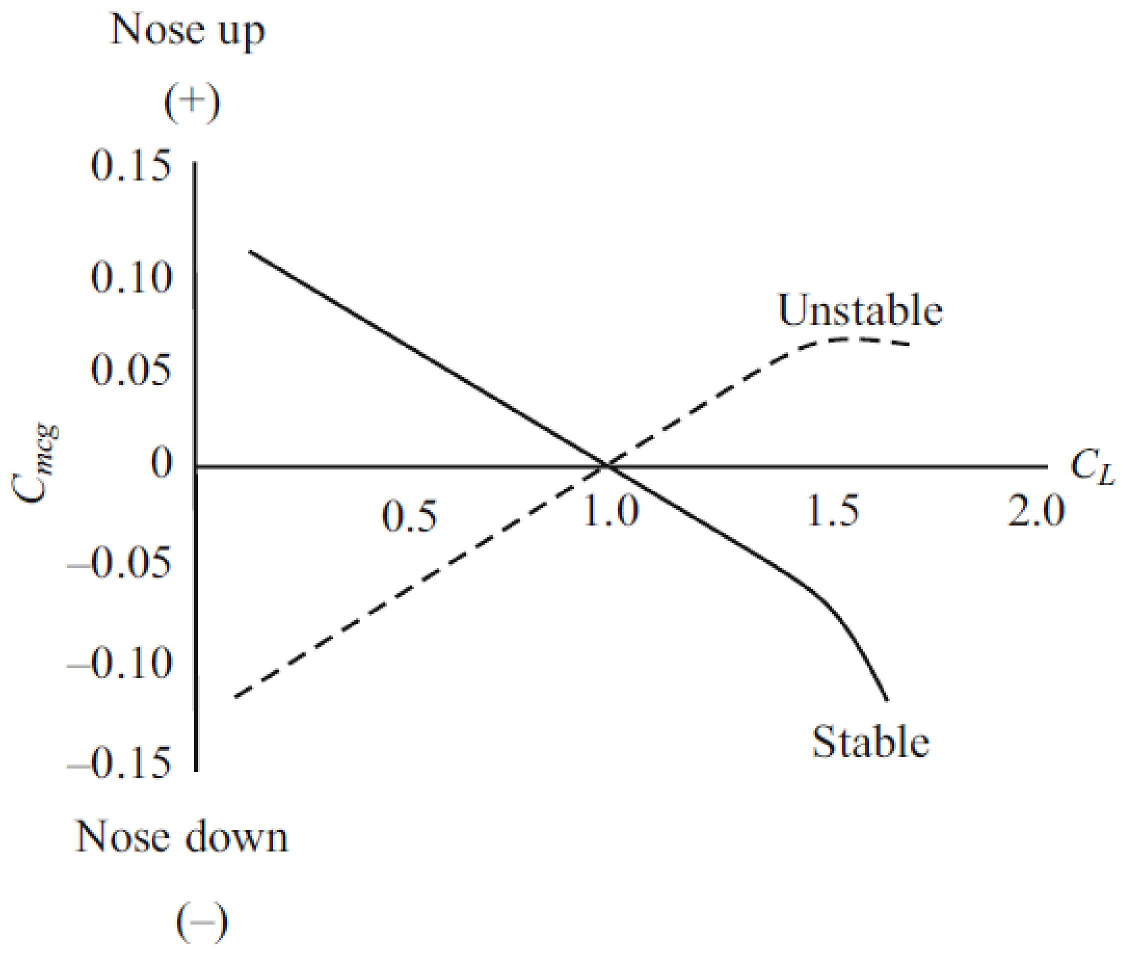


Figure 5.2 Pitching moment coefficient

LONGITUDINAL STABILITY

- For any flying object, whether an arrow or a complete aircraft, the center of gravity (CG) must be ahead of the aerodynamic center (center of pressure, CP) for the pitching moment-lift curve to remain negative, a condition for static stability as previously mentioned.
- Adding surfaces that produce lift and drag, such as horizontal and vertical stabilizers, behind the CG has the effect of moving the overall airplane aerodynamic center rearward, increasing stability.
- Placing a surface forward of the CG, such as a canard, does the opposite, reducing stability.

$$\frac{dC_M}{dC_L} = x_{cg} - x_{ac}$$

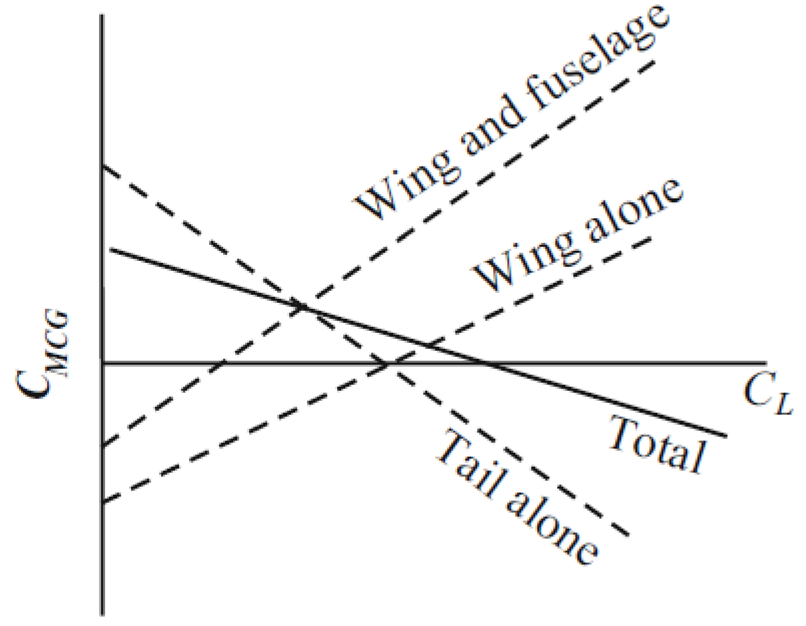


Figure 5.3 Contributors to pitching moment

LATERAL STABILITY

- Lateral stability is not as critical as longitudinal stability because a slight roll or yaw are not as destructive as pitch which, if uncontrolled for very long, can cause the air vehicle to stall and discontinue flying.
- Yaw (or directional) stability is easy to obtain by incorporating the proper amount of vertical fin or stabilizer area.
- The mathematics of yaw analysis is similar to the pitch case, except that the wing contributes almost nothing to yaw stability.
- The fuselage and vertical tail surfaces are the two major contributors.

LATERAL STABILITY

- As in the case of pitch, the side force coefficient versus yaw angle must have a negative slope for stability.
- The reasoning is identical to that previously used in the pitch case; the vertical fin must be able to create a restoring moment that minimizes the yaw angle caused by a side force disturbance.

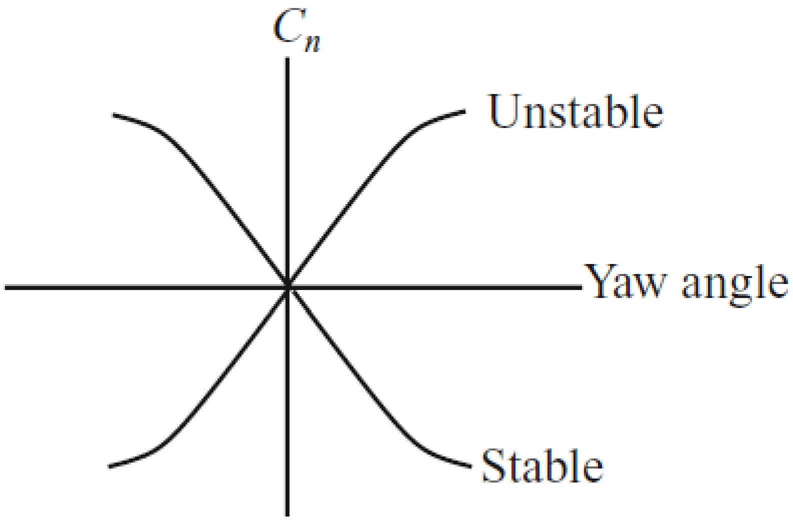


Figure 5.4 Directional stability

LATERAL STABILITY

- Roll stability is usually obtained by wing dihedral.
- The rolling moment due to sideslip is created by the dihedral angle that the wing makes with the fuselage.
- Wind impinging on a side slipping air vehicle will create a greater angle of attack (AOA) on the downwind wing than the upwind wing if the wings have dihedral.
- This causes the downwind wing to have greater lift than the upwind wing and cause it to roll in a direction so as to reduce the sideslip and hence create stability.
- The vertical location of the wing on the fuselage also creates roll stability, but the dominant factor is wing dihedral.

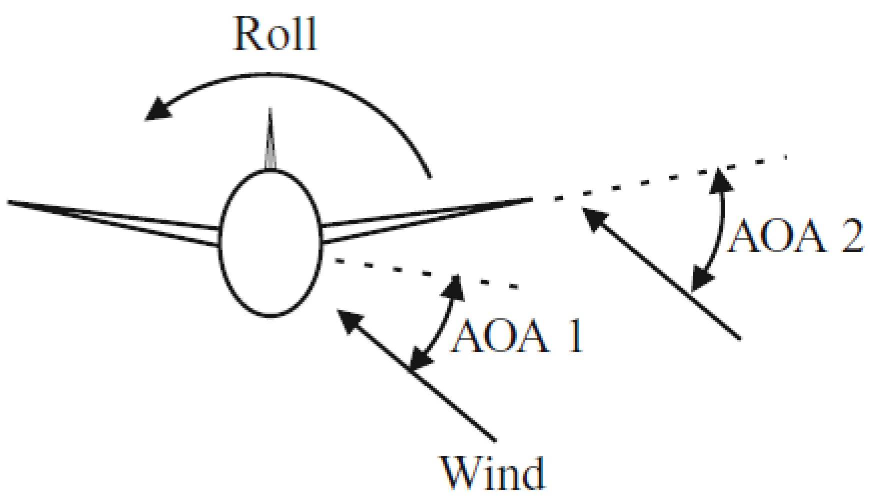


Figure 5.5 Roll stability

LATERAL STABILITY

- Adverse yaw is another stability concept, one hears much about.
- The British term “adverse aileron drag” is a more accurate name and makes the concept easier to understand.
- When the ailerons are deflected so as to create roll, they create drag that tends to yaw the air vehicle in
- the opposite direction of the turn caused by rolling.
- This results in an unbalanced condition that is alleviated by the application of rudder deflection to counteract the yaw.
- This, of course, is one of the primary reasons for having a rudder.
- A pilot can sense this unbalance but a UAV must automate the counter action in its flight control system.

DYNAMIC STABILITY

- To obtain dynamic stability, restoring forces must have the capability of absorbing energy from the system.
- Dynamic stability is created by forces that are proportional to the rate (velocity) of motion of the various surfaces such as wing, tail, and fuselage with the proportionality constant called a stability derivative.
- The stability derivative, when multiplied by the angular velocity of the vehicle, results in a force that usually reduces the angular velocity of the vehicle (i.e., absorbs energy). This phenomenon is called damping, which is a kind of friction.
- Because of the natural occurrence of friction in real systems, dynamic stability is usually, but not always, present if the system is statically stable.
- Dynamic instability arises when artificial means, such as an autopilot using feedback, are used to control the air vehicle. This can happen if the feedback in the control system is improperly designed or compensated and adds energy to the system that is out of phase wit the forces that are acting to correct divergent motion. This can lead to an amplification of the instability instead of damping.

SUMMARY - STABILITY

- The distance between the CP and CG has a profound effect on the stability of the air vehicle.
- Air vehicles that have a small distance between the CG and the CP are less stable than those with large separations.
- It is necessary for the CG to be forward of the CP for stability.
- The horizontal tail is an important control surface for both stability and the ability to control the vehicle.
- A larger distance of the tail, aft of the wing, results in greater control and stability.
- This is generally true but placing horizontal surfaces ahead of the CG (such as canards) can result in snappy control, but at the expense of stability.

CONTROL
AERODYNAMIC CONTROL

- The control of an air vehicle about the pitch, roll, and yaw axes is accomplished by the elevator, ailerons, and rudder, respectively.
- When performed by an onboard pilot flying "heads up" it involves a complex subconscious synthesis of the horizon seen outside the aircraft, the feel of the controls and aircraft and, literally, the feel of the "seat of the pants," which is the perceived net direction of the force on the pilots body due to the combination of gravity and the accelerations of the aircraft.
- For a UAV, the "feel" of the system via the feedback of the airframe and control surfaces is essentially nonexistent. (Artificial feel could be designed into the ground controls to give the controller some sensation of flying, but most UAVs have autopilots and electronic controls without artificial feel.)
- The forces created by the control surfaces are not fed back to the operator.
- Nevertheless, they must be analyzed so as to determine the proper response of the airframe and to determine the size of the actuators.

CONTROL
AERODYNAMIC CONTROL

- There are special flight conditions that require a specific motion or force from the control surfaces.
- For instance, the ability of the elevator to pitch the airframe (elevator control power) depends on the size, shape, and air velocity over it.
- During landing, when the air vehicle is usually flying very slowly, it is necessary that enough elevator effectiveness be available to keep the nose high so the vehicle does not gain speed.
- During a catapult launch, the speed also is low (near stall) and if the vehicle is disturbed, there must be enough control to maintain its attitude until the appropriate airspeed is obtained.
- The elevator must also be of a size and location to lift a nose wheel off the ground while the main gear is still on the runway during a conventional takeoff run.

CONTROL
PITCH CONTROL

- A pitching moment is generated by changing the lift coefficient of the tail surface by deflecting the elevators as shown in Figure 5.6.
- The elevator deflection also determines the acceleration (*g*'s) the airplane can generate and consequently the radius of turn.
- Since the lift always is perpendicular to the wing, when the aircraft is banking in a turn, the lift is tilted at an angle to the vertical and only the vertical component is available to oppose the downward force due to the weight of the aircraft.

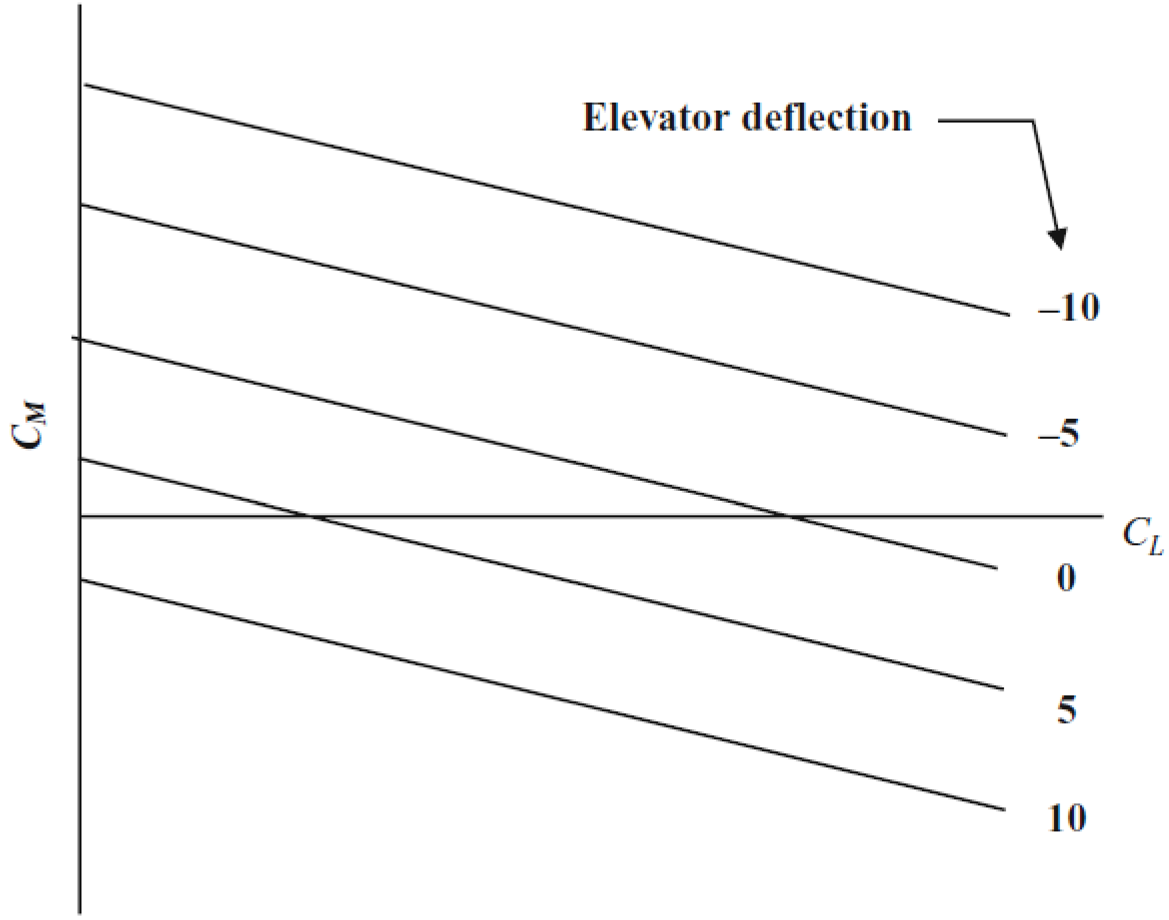


Figure 5.6 Pitch control moment versus elevator deflection

CONTROL
PITCH CONTROL

- As a result of this, the AOA must be increased to increase the total lift until its vertical component balances the weight.
- If this is not done the aircraft will lose altitude during the turn.
- To increase the AOA, up-elevator is applied by the pilot or autopilot.
- Thus, for a proper turn at constant altitude, the rudder is deflected to yaw the aircraft and the "stick" is moved to the side and pulled back to bank the aircraft and increase the AOA. This is called a "coordinate turn."
- An unmanned system must behave the same way that a piloted system would when turning and the "coordination" must be built into its flight control system

CONTROL
LATERAL CONTROL

- Ailerons are designed to create a roll. Roll control is necessary to turn.
- As previously discussed, a combination of rudder and horizontal stabilizer control is used to obtain balanced flight in a turn.
- Rudder control also is used for controlling yaw.
- All of the various flight conditions which a UAV may encounter must be investigated so that the control surfaces can be designed to the proper size and location.
- This usually requires a determination of the balance of forces and a simple integration of Newton's laws for air-vehicle moments.
- A complete dynamic analysis of the motion of the air vehicle caused by deflection of the control surfaces is a much more complex problem, requiring the use of a computer simulation.

AUTOPILOTS

- The method almost universally applied for the control of today's UAVs is use of an automatic, electronic control system in the form of an autopilot.
- Electronic control systems employ a feature called feedback or closed-loop operation. The actual state of the UAV flight path, attitude, altitude, airspeed, etc. is measured and electrically fed back and compared to (subtracted from) the desired state.
- The difference, or error signal, is amplified and used to position the appropriate control surface, which, in turn, creates a force to cause the air vehicle to return to the desired state, driving the error signal to zero.

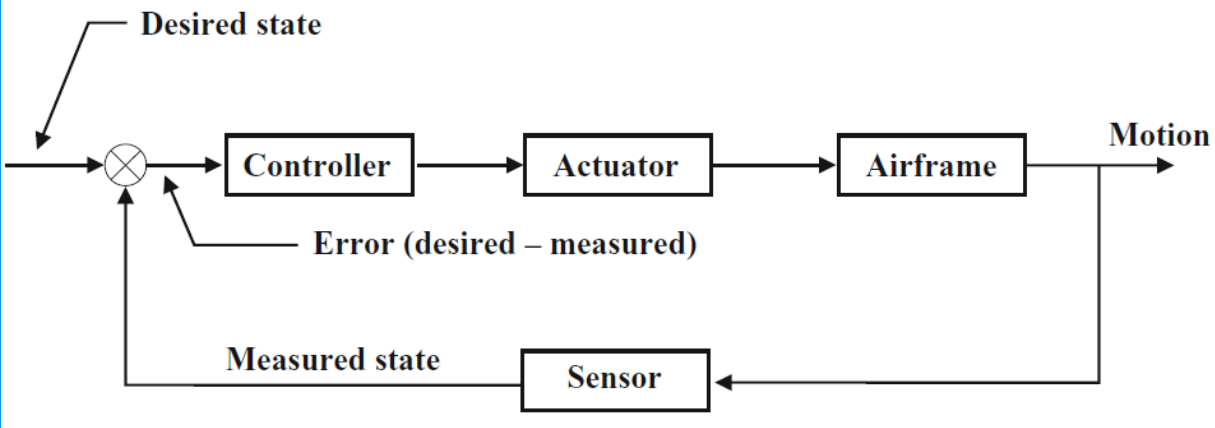


Figure 5.7 Block diagram of control loop

AUTOPILOTS
SENSOR

- The sensors measure the air vehicle's attitude (vertical/directional gyro), angular rate (rate gyros), airspeed (Pitot-static system), heading (compass), altitude (barometer or radar altimeter), and other functions as desired or necessary.
- The measured attitudes, altitudes, rates, etc. are compared to the desired states and if they deviate beyond a prescribed amount an error signal is generated, which is used to move a control surface such that the deviation is eliminated.
- The comparison function is usually done in a controller.

AUTOPILOTS
CONTROLLER

- The controller contains the necessary electronics to generate the error signal described above, amplify it and prepare it for the actuators.
- In addition, the modification and combining of signals from the different axes is accomplished in the controller.
- The controller also usually contains the electronics for processing commands and housekeeping outputs of the flight control system.

AUTOPILOTS
ACTUATOR

- The actuators produce the force necessary to move the control surfaces when commanded as a result of signals coming from the controller.
- Actuators used in large aircraft are usually hydraulic, but UAVs often use electric actuators, thereby obviating the need for hydraulic pumps, regulators, tubing, and fluid, all of which are heavy and often leak.

AUTOPILOTS
AIRFRAME CONTROL

- As the control surfaces move, they create forces that cause the air vehicle to respond.
- The sensors sense this response, or air-vehicle motion, and when the attitude, speed, or position fall within the prescribed limits, their error becomes zero and the actuators in turn cease to move the surfaces.
- The error signal is compensated so that the desired position or attitude of the air vehicle is approached slowly and will not overshoot.
- The system continuously searches for and adjusts to disturbances so that the air vehicle flies smoothly.
- The navigation system operates in much the same manner but the sensors are compasses, inertial platforms, radar, and GPS receivers.

AUTOPILOTS
INNER AND OUTER LOOPS

- Primary stabilization is accomplished in what is known as the inner loop, and basically maintains the air vehicle in its prescribed attitude, altitude, and velocity state.
- In addition, there is an outer loop that performs the task of maneuvering and navigating the air vehicle.
- The outer loop is also used to capture guidance beams for electronically-assisted or automatic recovery.
- A block diagram of a feedback control system showing both the inner and outer loops is shown in Figure 5.8.

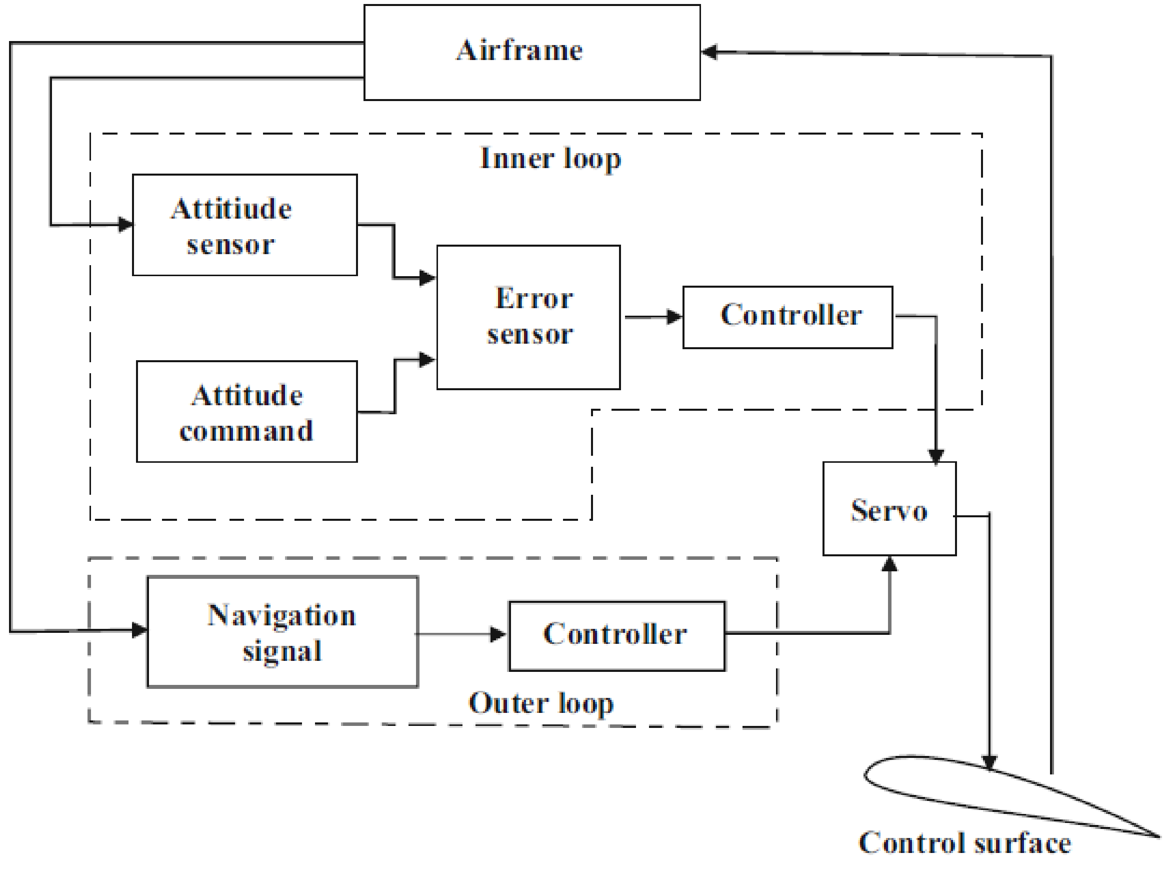


Figure 5.8 Flight control system block diagram

AUTOPILOTS
FLIGHT-CONTROL CLASSIFICATION

- Automatic flight-control systems are classified on the basis of the number of axes they control. (All of these systems also can incorporate throttle control to maintain a desired airspeed, as well as to control altitude.)
- *Single axis*:
- A single-axis system usually controls motion about the roll axis only.
- The control surfaces forming part of this system are the ailerons, and such a system is often called a "wing leveler."
- The "pilot" in the ground control station can inject commands into the system enabling him to turn the air vehicle and thereby navigate the vehicle.
- Sometimes signals from the magnetic compass or a radio beam are used to maintain a magnetic course or heading automatically.
- This type of operation is part of the outer loop, which will be discussed later.

AUTOPILOTS
FLIGHT-CONTROL CLASSIFICATION

- *Two axis*:
  - Two-axis control systems usually control the air vehicle about the pitch and roll axes.
  - The control surfaces used are the elevator and the ailerons, although rudders alone are sometimes used as “skid to turn” devices.
  - With pitch control available, the altitude of the air vehicle can be maintained in straight and level flight.
  - Steep turns, which lead to a loss in altitude when using roll control only, can be made without that loss by controlling pitch attitude.

AUTOPILOTS
FLIGHT-CONTROL CLASSIFICATION

- *Three axis*:
  - As the name implies, a three-axis system controls the air vehicle about all three axes and incorporates the use of the rudder for yaw control.
  - Some UAVs do not use a three-axis system.
  - This reduces cost without much reduction in capability because yaw control does not contribute significantly to the overall system (only coordination of a turn with the rudder).
  - If missiles and other ordnance are to be used with the UAV, yaw control (a three-axis control system) becomes more attractive.

AUTOPILOTS
OVERALL MODES OF OPERATION

- In addition to maintaining the attitude and stabilizing the air vehicle, the automatic flight control system can accept signals from onboard sources or from the ground (or satellite) to control the flight path, navigate, or conduct specific flight maneuvers.
- Such an operation is accomplished through the outer loop.
- The provision of these signals is called coupling, and their operation is called "mode of operation."
- For instance, the "air-speed mode" means that the air-vehicle speed is controlled or held constant automatically.
- This requires a sensor to measure the airspeed. Attitude mode means that the air-vehicle attitude in pitch roll and yaw is automatically maintained using gyros or other devices.
- Automatic mode implies that the air vehicle is completely controlled automatically and manual mode implies human intervention.

AUTOPILOTS
OVERALL MODES OF OPERATION

- In some cases, switching from one mode to another is automatic; thus, after intercepting a glide slope beam, the pitch channel is switched from altitude hold to glide slope track and the air vehicle automatically flies down the glide slope beam.
- The outer control loop includes the human operator, if there is one, and implements the operational control of the air vehicle.
- Operational control also includes the control of any payloads and the overall direction of the mission.

AUTOPILOTS
SENSORS SUPPORTING THE AUTOPILOT
ALTIMETER

- It is often important for the air vehicle to fly at a constant altitude and airspeed.
- To meet this requirement, or to provide an automatic leveling off when a desired altitude is reached, a barometric sensing device is used in the altitude-hold mode.
- The sensor consists of a pressure transducer connected to a partly evacuated chamber, an amplifier, and a follow-up motor.
- The partially evacuated chamber is subject to changes in static pressure when the air vehicle changes altitude, causing it to expand or contract and move a pickoff element that generates an electric current proportional to the position of the pickoff element and hence the static pressure or altitude.
- This current is amplified and sent to the pitch control channel to operate the elevator actuator and thereby restore the air vehicle to the desired altitude.
- The change in static pressure will also cause the follow-up motor to move the pickoff element in the opposite direction to reduce the error signal to zero.

AUTOPILOTS
SENSORS SUPPORTING THE AUTOPILOT
AIRSPEED SENSOR

- Airspeed sensors use static pressure sensors in addition to dynamic pressure sensors called Pitot tubes.
- The only difference between altitude sensors and airspeed sensors is that an airspeed sensor requires a differential between static pressure and dynamic pressure.
- The chamber, instead of being sealed, is open to a source of dynamic pressure (Pitot tube) and static pressure is admitted to the sealed container in which the entire assembly is located.
- The chamber expands or contracts from the pressure differential created by a change in airspeed.
- The rest of the system is identical to the altitude hold system, and the airspeed error signal is sent to the pitch axis and engine throttle control.

AUTOPILOTS
SENSORS SUPPORTING THE AUTOPILOT
ATTITUDE SENSORS

- Attitude hold usually is accomplished by measuring the rate of change in the air-vehicle attitude, using a device that maintains its attitude in inertial space, called a gyroscope ("gyro").
- At a minimum, it is necessary to measure the pitch of the air vehicle.
- A yaw gyro is added when a second axis is required, and a full, three-axis system adds a roll gyro.
- Gyros add to the cost of a system but are necessary when precise attitude control is required for accurate target location.
- The gyros associated with an autopilot are not generally used directly to measure attitude versus inertial space.
- Rather, each gyro generally is used to measure the rate of change of attitude in one axis and the rate of change is integrated electronically to estimate the present attitude.
- Various indirect ways of measuring the direction of gravity are used to correct accumulated errors and keep the estimate of pitch and roll from drifting too far from the earth's inertial frame.
- In this application, the sensors are called "rate gyros."
- Rate gyros are not suitable for long-term navigation. If that function is required a higher quality inertial reference is required.

AUTOPILOTS
SENSORS SUPPORTING THE AUTOPILOT
USE OF GPS

- The global positioning system (GPS) makes it possible to determine altitude, airspeed, attitude, and air-vehicle position based on satellite navigation signals rather than the variety of mechanical sensors previously required.
- However, the update rate for GPS measurements is not sufficient to support the inner loop of the autopilot, so rate sensors still are required for that function.
- However, GPS provides an accurate long-term reference that can be used to avoid drift in the short-term estimates and for navigation