Inertially Stabilized Platforms for Optical Imaging Systems

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TRACKING DYNAMIC TARGETS WITH MOBILE SENSORS

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Optical imaging sensors, such as television or infrared cameras, collect information about targets or target regions. It is thus necessary to control the sensor's line-of-sight (LOS) to achieve accurate pointing. Maintaining sensor orientation toward a target is particularly challenging when the imaging sensor is carried on a mobile vehicle or when the target is highly dynamic. Controlling an optical sensor LOS with an inertially stabilized platform (ISP) can meet these challenges.

BACKGROUND

An ISP is a mechanism, typically involving gimbal assemblies, for controlling the inertial orientation of its *payload*. A *target tracker* is a process, typically involving image processing techniques, for detecting targets in optical imagery. This article describes the use and design of ISPs and target trackers for imaging optical sensors. In some configurations, the optical sensor is mounted directly into the ISP, whereas, in other configurations, the ISP controls other optical elements such as mirrors. A properly designed ISP precisely controls the sensor LOS despite intentional maneuvers, inadvertent motion, and additional disturbances.

Some applications may not involve a specific target. Rather, the goal may be to drive the sensor LOS toward precalculated orientations or surveillance regions. In this case, additional equipment defines the desired orientation without target feedback information. Although the commanded LOS orientation may not correspond to a specific target, the challenges for the ISP design are similar, particularly when the sensor is carried on a mobile vehicle.

Even when targets are to be tracked, however, system operation typically commences without target information. In this scenario, the LOS is initially controlled without pointing feedback until a target is located and the tracker completes the acquisition process. Once the target is acquired, the tracker provides the commands that subsequently control the ISP.

When an optical sensor is installed within an ISP, the sensor's LOS is manipulated relative to the host vehicle. However, in long-range applications, such as satellites or exoatmospheric vehicles, the optical sensor may be *strapped down*, that is, rigidly fixed, so that the entire vehicle must be stabilized to achieve sensor pointing.

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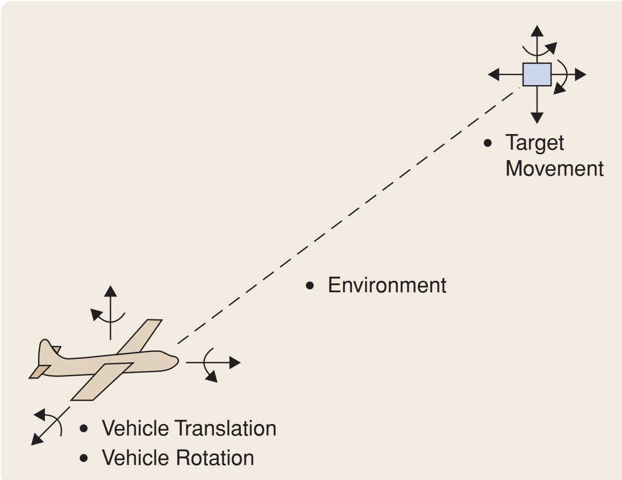

FIGURE 1 Stabilization-tracking system challenges. Inertially stabilized platforms enable optical imaging sensors to acquire and track targets so that clear images are captured despite relative motion between the target and optical sensor.

Although actuators that manipulate vehicles may be different from those that control mechanical platforms, the ISP technology is virtually identical.

Controlling LOS entails two equally important requirements. The LOS must be pointed in preselected or scenario-dependent directions toward a given target or target region and must be held steady in inertial space along the selected orientation. The performance metric for the first requirement is *tracking error*, while the metric for the second requirement is *jitter*.

The first fundamental objective of an ISP, when used with an optical imaging sensor, is to obtain good quality images of the target or target region. In simple terms, the first stabilization-tracking problem is, "What must be done so that the optical sensor produces clear, sharp images of its selected target?" As illustrated in Figure 1, three fundamental challenges arise, namely, target motion, host vehicle motion, and the operating environment.

Target Motion

Consider the problem of tracking a dynamic target. If the orientation of a narrow field-of-view (FOV) optical sensor is fixed or otherwise uncontrolled, a mobile target can readily move outside of the FOV. Although translational motion, perhaps due to evasive maneuvers by the target, can cause loss of target tracking, target rotation can also introduce errors. If a highly asymmetric target image rotates within the sensor's FOV to a sufficient level that the target tracker no longer recognizes the target, then tracking may fail.

Host Vehicle Motion

Host vehicle motion can also introduce errors. Translation of the host vehicle can result in the target moving out of the sensor's FOV if the ISP does not adjust to accommodate changes in relative position between the target and host vehicle. Likewise, host vehicle rotational maneuvers in pitch, yaw, or roll can pull the LOS off the target if the ISP is coupled to the host vehicle. Vibration or small-amplitude motion of the host vehicle can also degrade (smear) the sensor's image.

Operating Environment

The environment can also impact tracking performance. In target-tracking applications, ISP control is based on optical information regarding target location collected by the sensor. Atmospheric conditions such as fog, smoke, or dust between the optical sensor and the target, as well as obscurations due to hills and trees, can prevent the sensor from collecting information, thus resulting in loss of track. On the other hand, if advanced image processing operations within the tracker can maintain orientation during periods of target blanking, tracking can continue.

For most applications, the second fundamental objective of an ISP is to determine the location of the target with respect to a prescribed frame of reference. Thus, in simple terms, the second stabilization-tracking problem is, "Where is the target?" Since the ISP controls the LOS so that it points toward the target, measurement of the LOS orientation directly yields the target's angular location. Position measurement devices, called *pickoffs*, installed within the ISP mechanism determine the target location in the host vehicle's reference frame. However, if the desired reference frame is an inertial reference, then an inertial measurement unit (IMU) or inertial navigation system (INS) is first used to measure the vehicle's inertial orientation. The IMU/INS measurements are combined with pickoff measurements of LOS orientation with respect to the vehicle to yield target location with respect to the desired reference.

OPERATING PRINCIPLES

A typical ISP used to stabilize sensor LOS consists of an *electromechanical assembly*, which provides the physical interface between the optical sensor and the host vehicle, a *control system*, which manipulates the electromechanical assembly, and *auxiliary equipment*, which measures target location relative to the ISP reference system. We now look at each of these components.

Electromechanical Assemblies

An ISP electromechanical assembly is typically composed of gimbals that rotate either the sensor or the optical components of the sensor. At least two fundamental approaches can be used, namely, *platform stabilization* and *steering stabilization*.

In platform stabilization, illustrated in Figure 2, the entire payload rotates within a gimbal assembly to enable the sensor LOS to be altered relative to the host vehicle. The gimbal can be rotated by a direct-drive motor installed

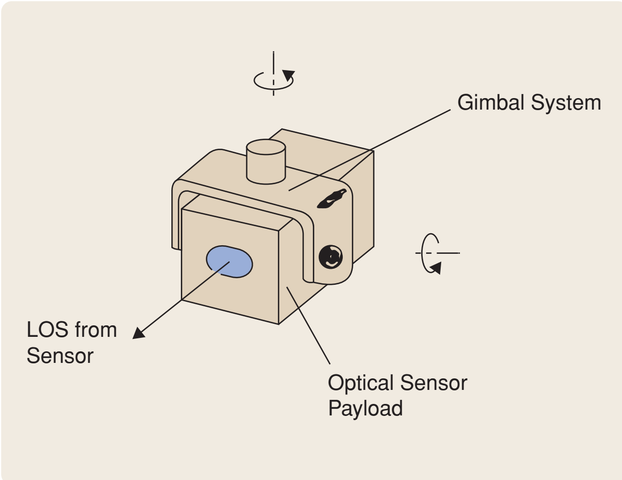

FIGURE 2 Platform stabilization. With platform stabilization, the optical sensor payload is mounted on a platform within a movable gimbal system, and the line of sight (LOS) is changed by moving the entire gimbal platform.

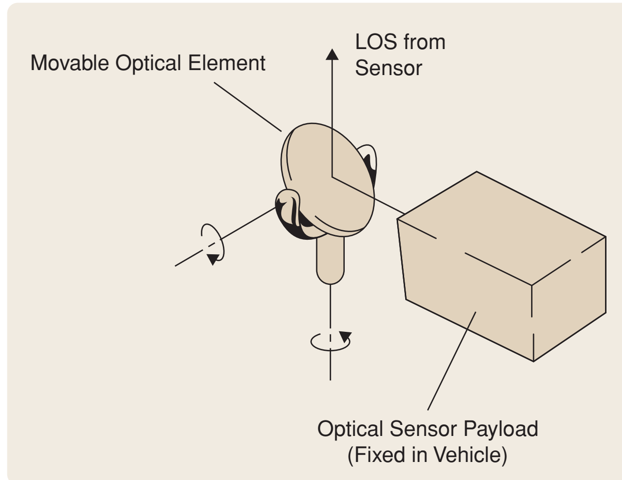

FIGURE 3 Steering stabilization. In steering stabilization, the optical sensor payload is fixed within the vehicle, and a movable optical element is installed within the optical path. The line of sight (LOS) is changed, or steered, by moving the optical element rather than the sensor.

on the gimbal axes or by a motor linked to the gimbal through a geartrain or a mechanical linkage such as a belt or chain. Platform stabilization is also called *mass stabilization* because the entire payload mass is stabilized. The LOS orientation is determined by the angular displacements of the gimbal assemblies. When the host vehicle maneuvers or vibrates, the gimbals, if operating properly, rotate in the opposite direction so that LOS orientation remains fixed with respect to inertial space. Gimbal motion thus directly determines LOS direction and image jitter.

On the other hand, *steering stabilization* moves optical elements, such as a reflecting mirror, to change the orientation of the LOS, while the sensor is fixed with respect to the host vehicle. In this arrangement, LOS orientation is determined indirectly through control of only a portion of the optical system. As illustrated in Figure 3, the geometric relationship between the mirror and the sensor determines the scene viewed by the sensor. When the target moves, the geometric relationship must be altered to maintain track. Likewise, if the host vehicle vibrates or maneuvers, the mirror must be controlled to cancel the effect of the vehicle motion. In this assembly, the nominal position of the mirror directs the LOS to the desired location, while additional motion compensates for disturbances that introduce jitter.

When using indirect steering stabilization, optical elements such as mirrors, wedges, prisms, and lenses are used to alter the LOS orientation. The steering element can be placed in various locations within the overall sensor optical path. In Figure 3, a plane mirror is installed in front of the imaging sensor in a *mirror-stabilization* arrangement. Approaches that control optical elements must take characteristics such as magnification into consideration [1].

Mass Stabilization Through Direct Drive

In a mass-stabilized system, the goal is to hold the payload's orientation steady in inertial space. A mass-stabilization gimbal with *direct drive* uses a torque motor mounted directly onto the gimbal axis without gears or belts. In an ideal mass-stabilized direct-drive system having no friction, cable flexure, imbalance, kinematic coupling, or additional disturbances, the sensor remains oriented in its initial position as a consequence of Newton's laws. Control of a mass-stabilized direct-drive system thus becomes an issue of how to best design the assembly to minimize the effect of disturbances introduced on the ISP.

The fundamental operation for a single gimbal of a mass-stabilized direct-drive system is illustrated by the free-body diagram in Figure 4(a). The direct-drive motor is installed within the gimbal so that the applied control torque causes the payload to accelerate in inertial space. The entire movable payload and its support packaging is modeled by the single inertia term J, which appears in the rotational dynamics

$$J\frac{d^2\theta_L}{dt^2} = T_M + T_D\,, \tag{1}$$

where θ_L is the angular orientation of the payload LOS, T_M is the command torque from the gimbal drive motor, and T_D is the net effect of all disturbance torques.

The fundamental control system feedback measurement is from a gyroscope (or *gyro*) mounted within the sensor package. The term "gyro" refers to a wide class of inertial sensors that measure angular rate or angular displacement in inertial space. In this article, unless otherwise noted, our discussion concerns gyros that measure angular rate. Since

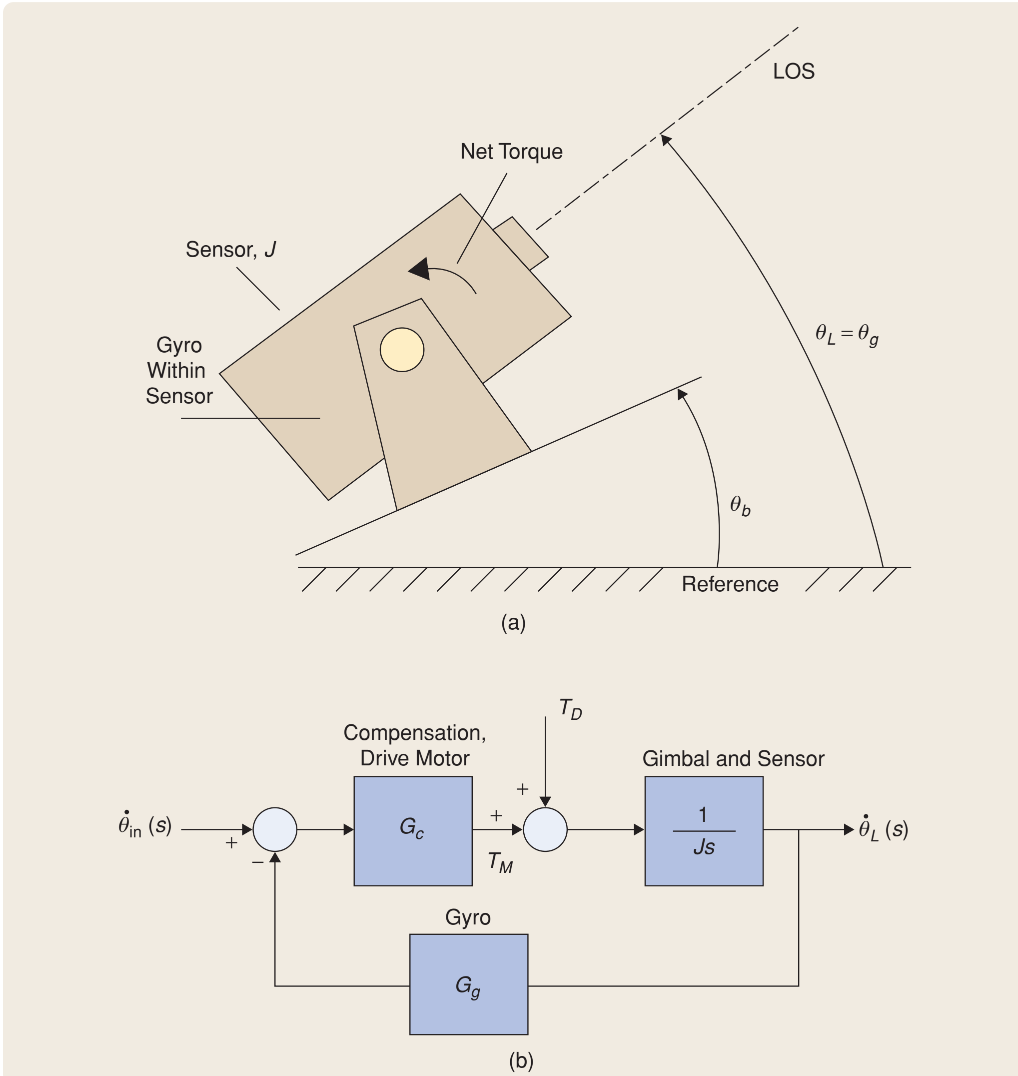

FIGURE 4 Mass-stabilized, direct-drive system. In a mass-stabilized direct-drive system (a), the drive motor is mounted directly onto the gimbal axis without gears, belts, or linkages. All disturbances in (b) are represented as torque disturbances T_D on the gimbal axes.

LOS is the essential performance variable, the gyro is precisely installed within the sensor package so that its measurement axis is always aligned with the LOS. The gyro thus directly measures inertial LOS rate.

The disturbance torque T_D is a torque-equivalent representation of all disturbances that can disrupt the behavior of the gimbal system. These disturbances, as described in "Torque Disturbances," include friction within the gimbal axes, spring flexure from electrical cables that cross the gimbal axes, imbalance effects, coupling from other gimbals, and host-vehicle motion coupling, as well as internal disturbances within the sensor. The control torque from the drive motor T_M is determined by the control loop selected by the designer. Taking the Laplace transform and rearranging (1) yields the LOS rate

$$\dot{\theta}_L(s) = (T_M + T_D)/Js, \tag{2}$$

where s is the Laplace variable. This equation is implemented in the block diagram in Figure 4(b). The control system consists of a gyro, which measures the LOS rate, and the combined compensation/drive motor, which produces the command torque T_M. The command torque is thus determined by the controller compensation in response to the combined command input and LOS inertial rate feedback.

The rate command input $\dot{\theta}_{\mathrm{in}}(\mathrm{s})$ to the control loop in Figure 4(b) controls the orientation of the gimbal assembly, thus enabling the LOS to track a target or move the LOS to a new orientation. It follows from Figure 4(b) that the closed-loop LOS behavior is determined by

$$\dot{\theta}_L(s) = \frac{\mathrm{G_c}/J}{s + \mathrm{G_c G_g}/J}\ \dot{\theta}_{\mathrm{in}}(\mathrm{s}) + \frac{1/J}{s + \mathrm{G_c G_g}/J} T_D, \tag{3}$$

where $\mathrm{G_g}$ is the transfer function for the gyroscope that measures LOS rate, and $\mathrm{G_c}$ is the feedback error-to-torque transfer function for the combined compensation/drive motor. The objective of the control system is to regulate the output LOS rate while minimizing the effects of external disturbances. This model ignores gyro and motor imperfections as well as electronic noise, but nevertheless illustrates the fundamental control objective, namely, to follow the rate-command inputs while rejecting disturbances.

Mass Stabilization Through Gear Drive

A mass-stabilized gear-driven system is similar to a mass-stabilized direct-drive system except that a motor and geartrain assembly are used to drive the gimbals. A direct-drive gimbal takes maximum advantage of Newton's laws since, in an ideal mass-stabilized direct-drive system (with no disturbances), the payload remains oriented in its initial position. However, when a gear drive is used, the geartrain inherently couples the host vehicle base motion into the payload. Consequently, even a frictionless system must compensate for LOS motions introduced by vehicle pitch, yaw, and roll motion. Although this unavoidable coupling is a disadvantage in a geartrain, a motor and geartrain are often essential when large-diameter bearings are used in a gimbal assembly. Large-diameter direct-drive torque motors are expensive, heavy, and often require custom fabrication. Moreover, a smaller gear arrangement is preferred when packaging constraints prohibit installation of a direct drive motor. Finally, gears can provide higher torques than would be feasible by a direct torque motor.

Figure 5(a) provides the free-body diagram for a gear-driven mass-stabilization system. As in the direct-drive configuration, the gyro provides a direct measurement of the sensor LOS. The payload is modeled as an inertia J_L with LOS angle θ_L. However, in a gear-driven configuration, additional variables are introduced, namely, the motor inertia J_m, the gear ratio (the ratio of the motor gear radius to the payload gear radius), and the motor angle θ_m. The dynamics of the gear-driven configuration are given by

$$J_m \frac{d^2\theta_m}{dt^2} = T_M - rF + T_{dm}\,, \tag{4}$$

$$J_L \frac{d^2\theta_m}{dt^2} = RF + T_{dL}\,, \tag{5}$$

Torque Disturbances

Although disturbances arise from diverse sources, the net effect can be described by an equivalent torque disturbance T_D, which simplifies ISP mathematical modeling. The most critical performance metric for an ISP is therefore torque disturbance rejection (see Figure 11). Common ISP disturbances [2]–[5] are summarized below. Analytical model predictions of these disturbances are frequently inadequate for a precision ISP designed for ultra-low LOS jitter performance.

Coulomb friction within the electromechanical assemblies is typically the dominant disturbance. Friction arises from surface interactions between and within the rotating bearings of the gimbals, environmental and electromagnetic interference seals, and brush contact in brush-type motors (or similar phenomena in hydraulic or pneumatic actuators).

Spring torques due to flexure, compression, or stretching of electrical cables between the payload and the host vehicle produce disturbances. In addition, some payloads require coolant lines or electrical or mechanical connections to the host vehicle.

Imbalance produces LOS jitter when the payload center of gravity is not centered on an axis of rotation for the gimbals. Linear vibration, acting through the lever arm of the center of gravity offset, thus produces torque disturbances.

Vehicle motion (kinematic) coupling occurs when host vehicle maneuvers (pitch, yaw, roll) couple into gimbal mechanisms. The ISP orientation, relative to the host vehicle, clearly must change during such maneuvers, and the necessary change can be accounted by transforming the vehicle maneuvers into equivalent torque disturbances for the gimbal mechanisms.

Intergimbal coupling occurs when cross-products of inertia produce disturbances in one gimbal due to motion in another gimbal. Another inter-axis coupling is *gyroscopic torques*, where the product of rates in two axes produce disturbances in a third axis.

Internal disturbances, including noise in the control loop components such as actuators, electronics, and gyros, can also be represented by an equivalent torque disturbance. *Noise* is usually defined as unpredictable disturbances; but it can include sources such as electric motor cogging, where the motor rotor interacts with the magnetic pole faces of the motor. Another internal disturbance is *shaking forces*, which originate from components within the payload with moving parts; for example, cryogenic coolers or scanning mirrors within a video or IR camera.

Structural flexure occurs when a payload or gimbal assembly bends or deforms due to external disturbances or vibration. Jitter from structural bending is typically measured by the gyro, and control action is taken to reduce the effect. However, structural flexure can also occur in parts of the payload/gimbal assembly not measured by the gyro.

Environmental disturbances are exhibited as both direct and indirect interactions. If an ISP and payload are exposed to the vehicle's aerodynamic wind stream, direct buffeting occurs. Indirect disturbances include changes in temperature and ice buildup on the ISP. Temperature variations can introduce changes in other disturbances such as friction or inter-gimbal coupling. Ice buildup can change gimbal balance so that vibration coupling is further aggravated.

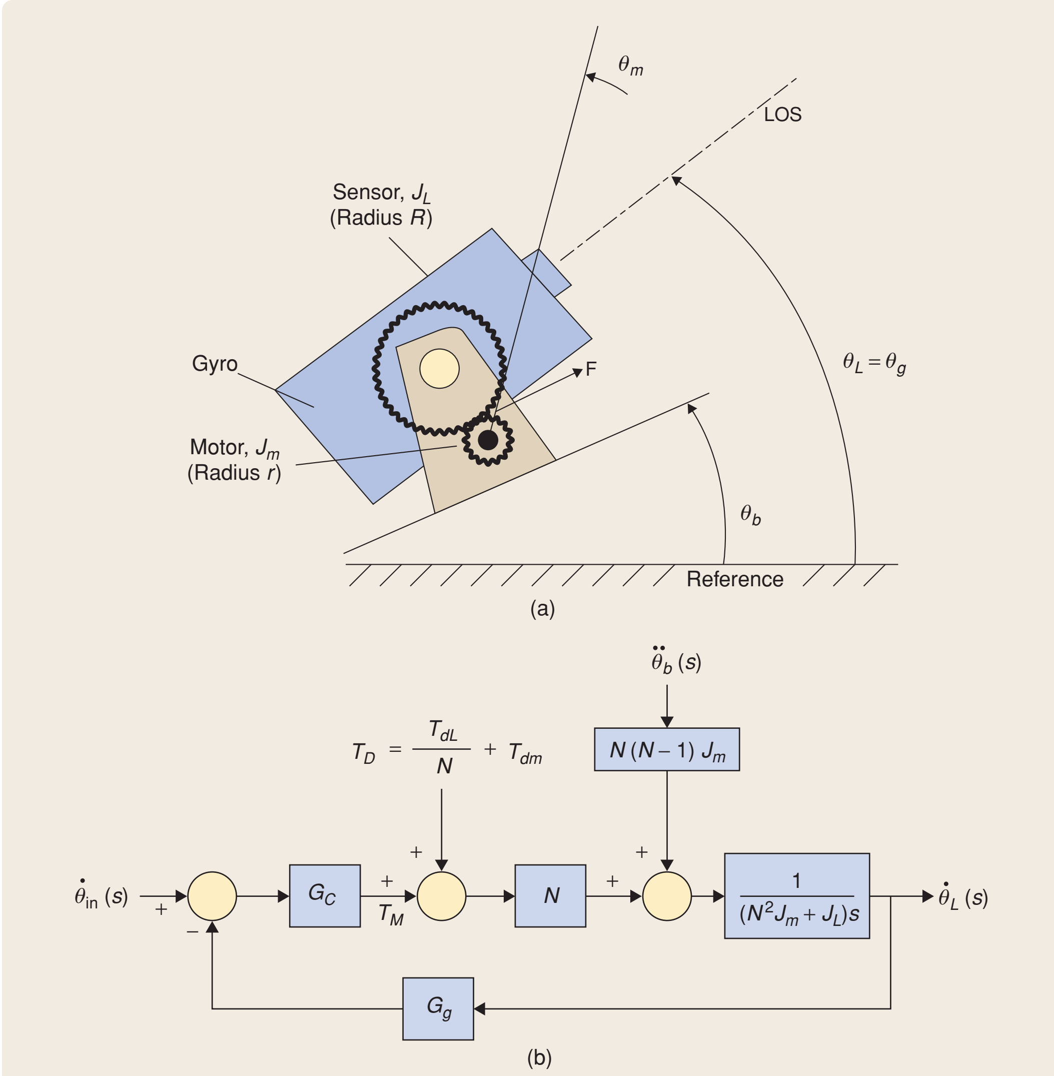

FIGURE 5 Mass-stabilized, gear-driven system. In a mass-stabilized gear-driven system (a), the motor drives the gimbal through gears, belts, or linkages. In addition to torque disturbances T_D in (b), the body motion $\ddot{\theta}_b$ of the host vehicle directly couples into the LOS.

where F is the interacting force between meshing gears, r is the motor gear radius, and R is the radius of the gear attached to the gimbal. The torque disturbances T_{dL} acting on the payload bearings include friction, cable flexure, imbalance, and interactions with the environment to which the payload is subjected. The disturbance torque T_{dm} acting on the motor is due to cogging, bearing friction, and imperfections in the motor.

The kinematic relations for the gear-gimbal assembly, which define the relationships among the payload, motor, and host vehicle include

$$\theta_L = \theta_{L/b} + \theta_b\,, \tag{6}$$

$$\theta_m = \theta_{m/b} + \theta_b\,, \tag{7}$$

$$\theta_{m/b} = N\,\theta_{L/b}\,, \tag{8}$$

where $\theta_{L/b}$ is the orientation of the gimbal (and the LOS) with respect to the host vehicle, and $\theta_{m/b}$ is the relative motion of the motor with respect to the vehicle. Equation (8) relates the payload to the motor when the reference is the host vehicle, where N is the gear ratio R/r.

Taking Laplace transforms of (4) and (5) and using the kinematic relationships (6)–(8) yields

$$\dot{\theta}_L(s) = \frac{[NT_M + NT_{dm} + T_{dL} + N(N-1)\,J_m\ddot{\theta}_b(s)]}{(N^2\,J_m + J_L)s}\,, \tag{9}$$

which corresponds to (2) for a direct-drive configuration as illustrated in Figure 5(b). As in direct-drive mass stabilization, the gyro measures the LOS rate to generate drive torques to counteract disturbances. When Figure 5(b) is used to determine LOS behavior, the LOS rate is determined by three factors

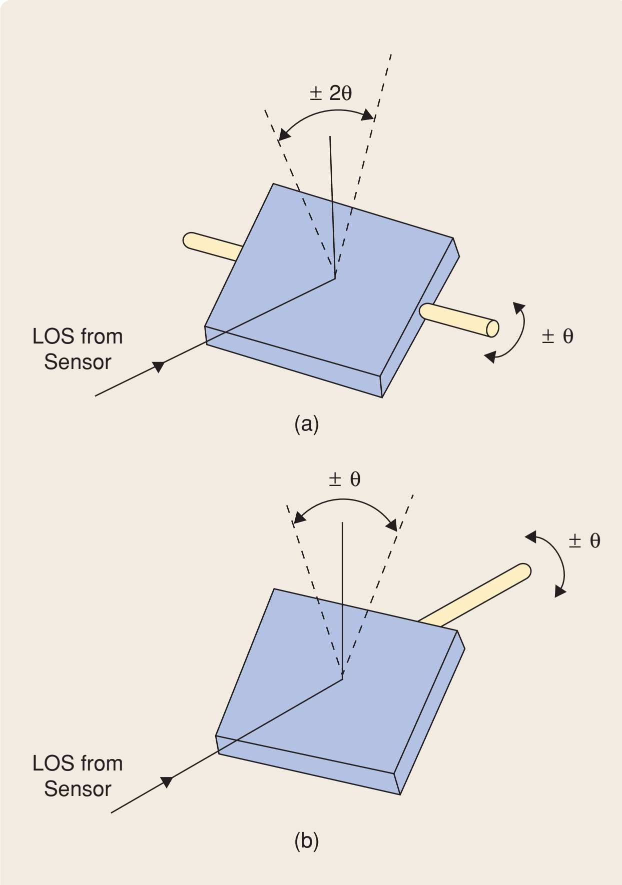

FIGURE 6 Mirror dynamics and optical doubling. In (a), rotation of a plane mirror perpendicular to the line of sight (LOS) moves the LOS by twice the angle of rotation of the mirror, a phenomenon known as optical doubling. In (b), rotation around the LOS (called periscope rotation) moves the LOS through an equal angle.

$$\dot{\theta}_L(s) = \frac{\mathrm{G_c}/J'}{s + \mathrm{G_c G_g}/J'}\,\dot{\theta}_{\mathrm{in}}(s) + \frac{(N-1)J_m/J'}{s + \mathrm{G_c G_g}/J'}\,\ddot{\theta}_b(s) + \frac{1/J'}{s + \mathrm{G_c G_g}/J'}T_D\,, \tag{10}$$

where $J' = NJ_m + J_L/N$ and $T_D = T_{dm} + T_{dL}/N$. Comparing (10) for gear-driven stabilization to (3) for direct-drive implementation reveals that the gear-driven configuration has two undesirable inputs, namely, torque disturbances T_D as well as a coupling of base motion from vehicle angular acceleration $\ddot{\theta}_b$. Therefore, the key distinguishing difference between direct- and gear-drive implementations is the unavoidable inherent base motion coupling in the gear-driven configuration. This coupling exhibits itself as a tendency for the LOS to follow vehicle motion. Obviously, the control loop must compensate for this coupling as well as the torque disturbance represented by the term T_D.

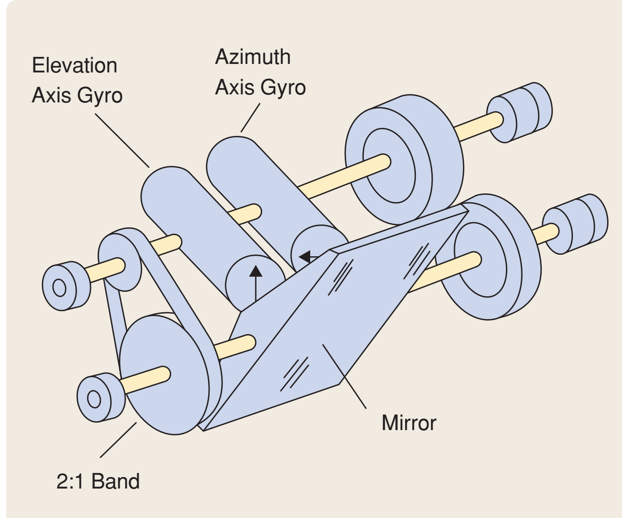

FIGURE 7 A 2-to-1 linkage between gyros and mirror. Since this 2-to-1 linkage rotates the gyro through twice the angle of the mirror, the gyro measures LOS rather than mirror motion as in mechanisms with optical doubling.

Mirror Stabilization

A plane mirror mounted in front of a sensor, as illustrated in Figure 3, illustrates the steering stabilization approach. A phenomenon that must be considered when using steering stabilization is the possibility that motion of the steering apparatus may not produce equal motion of the image on the optical sensor. The specific relationship between input mechanical rotation and LOS output motion depends on the location of the steering apparatus within the optical chain, the magnification of the optics, and other factors [1], [6]. For a plane mirror installed in front of the sensor, this phenomenon has a doubling effect as shown in Figure 6(a). Rotating the mirror through a given angle about the axis perpendicular to the LOS results in a LOS rotation equal to twice the angle of the mirror rotation, a phenomenon referred to as *optical doubling*. Special provisions must be included in the control mechanism to accommodate this doubling.

Although rotation of the mirror about an axis perpendicular to the LOS produces optical doubling, this is not the case for rotations *around* the LOS axis, as illustrated in Figure 6(b). In this case, mirror rotation results in an equal rotation of the LOS. This arrangement, which is essentially a periscope-type steering head, permits scanning the LOS over a full 360°. However, the scanning motion is accompanied by rotation of the image as it is transmitted from the mirror to the sensor. This rotation can be compensated by an additional optical de-rotation element, such as a prism, inserted in the optical path or by rotating the sensor itself.

Since mirror rotation and LOS rotation are equal in periscope-type steering, LOS control for periscope rotation is straightforward and not unlike mass stabilization. However, control of the axis that yields optical doubling cannot simply

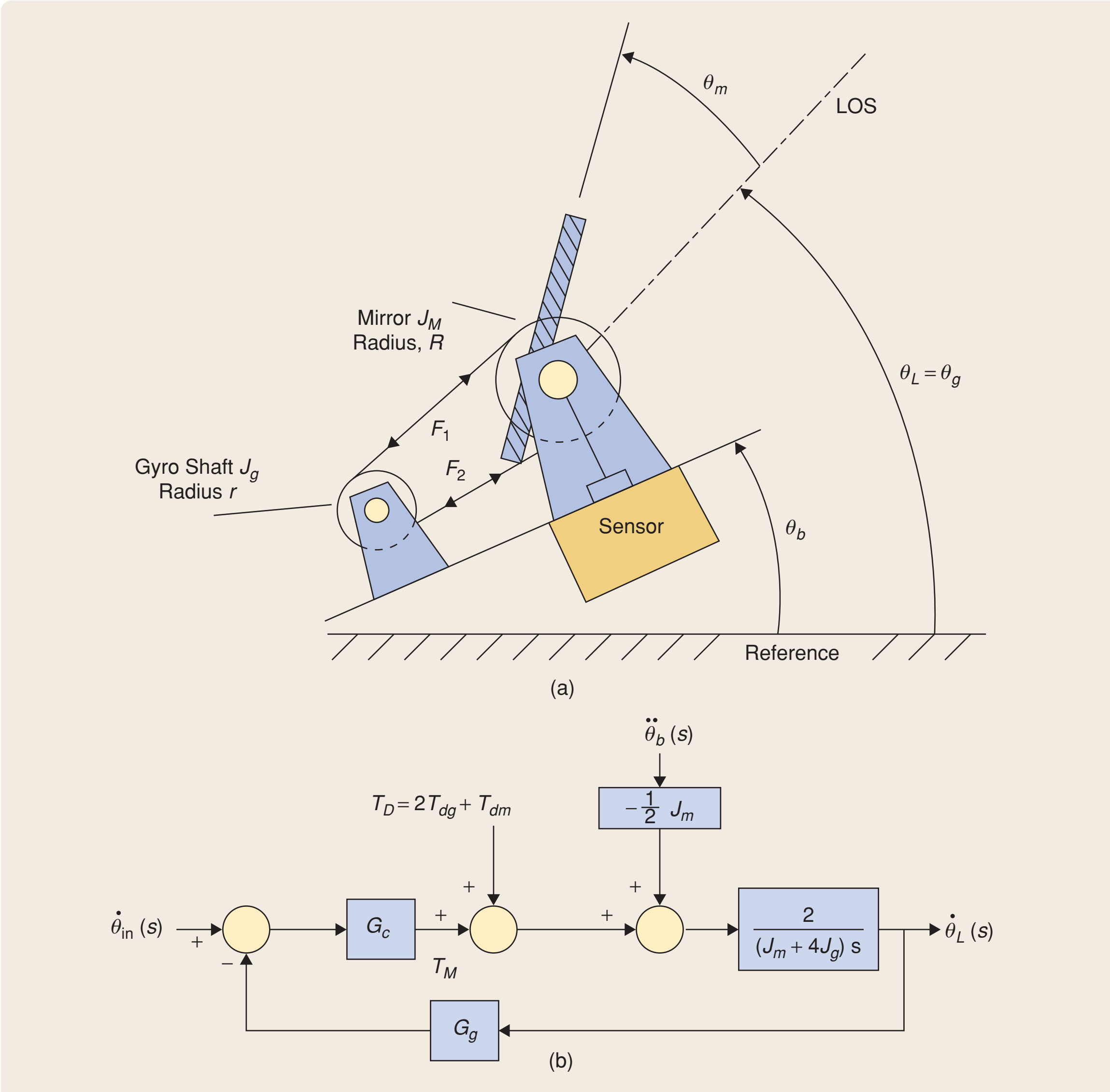

FIGURE 8 Stabilized mirror system. In a stabilized mirror system (a), the line of sight (LOS) is controlled by driving the mirror rather than the sensor. In addition to torque disturbances T_D (b), body motion $\ddot{\theta}_b$ of the host vehicle directly couples into the LOS.

be designed as if the axis were a mass-stabilized system. Rather, to compensate for the doubling effect, the mirror must be rotated by half of the required angular correction. This rotation can be achieved by a mechanism in which a stabilized element is linked to the mirror with a division ratio of 2:1. A typical arrangement, shown in Figure 7, has two shafts tied together by steel bands or low compliance cables. The ratio of the radii of the two shafts to which the band is connected is 2:1. Thus, the second shaft, moving through twice the angle of the mirror shaft, corresponds exactly to the LOS. Mounting the gyro on the shaft thus enables the gyro to correctly measure the LOS rate and provide feedback to be used to stabilize the LOS.

Figure 8(a) is a free-body diagram of the stabilized plane mirror and the 2:1 band coupling mechanism. The key system parameters are the respective radii and inertias of the mirror and gyro shafts. In concept, the motor that drives the banded mirror and gyro shaft assembly can be installed on either axis. In practice, this decision is affected by considerations such as package layout limitations. Assuming the motor is installed on the mirror shaft, the equations of motion are

$$J_M \frac{d^2\theta_M}{dt^2} = T_M - R(F_1 - F_2) + T_{dm}, \tag{11}$$

$$J_g \frac{d^2\theta_g}{dt^2} = r(F_1 - F_2) + T_{dg}, \tag{12}$$

where T_M is the motor torque determined by the control loop. The disturbance torque T_{dm} represents all of the factors that influence the ability of the control loop to control the mirror shaft (including friction torques), while T_{dg} represents all of the factors that affect the gyro shaft. The respective radii of the shafts are R and r, while F_1 and F_2 are the forces applied to the coupling band by the shafts.

The kinematic relationships for mirror stabilization are similar to those for gear-driven mass-stabilization with the special restriction that the ratio of the shaft radii R/r is 2:1, in which case

$$\theta_g = \theta_{g/b} + \theta_b, \quad (13)$$

$$\theta_M = \theta_{M/b} + \theta_b, \quad (14)$$

$$\theta_{g/b} = 2\theta_{M/b}. \quad (15)$$

Because the 2:1 assembly is designed so that the gyro shaft moves in the same manner as the LOS, the gyro angle is equal to the LOS angle, that is,

$$\theta_L = \theta_g. \quad (16)$$

Taking the Laplace transform of (11) and (12) and using (13)–(16) yields the LOS rate

$$\dot{\theta}_L(s) = \frac{[2T_M + 2T_{dm} + 4T_{dg} - J_M\ddot{\theta}_b(s)]}{(J_M + 4J_g)s}. \quad (17)$$

Incorporating (17) into the control system block diagram of Figure 8(b) and solving for the LOS rate yields

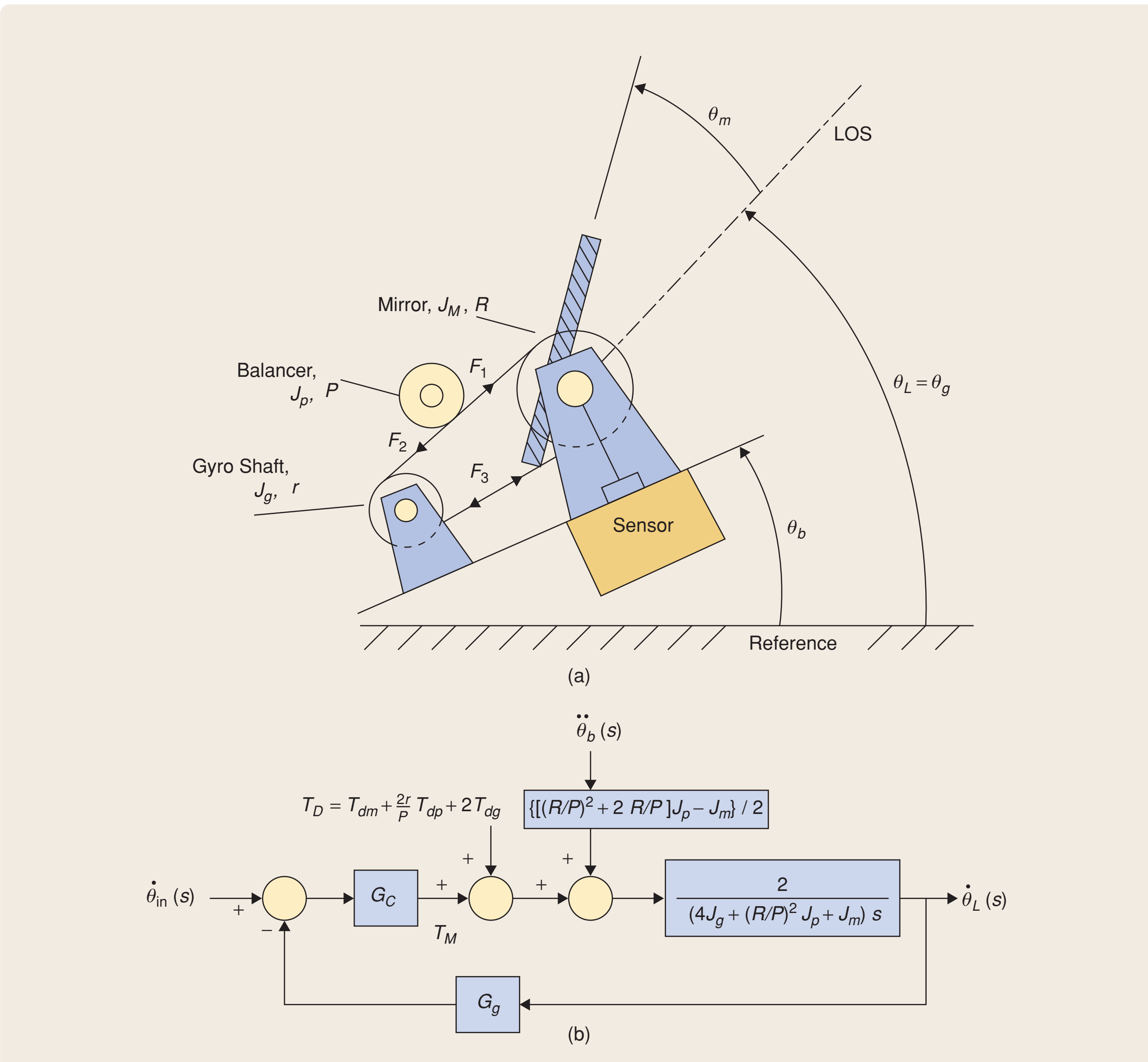

FIGURE 9 Stabilized mirror system with inertial balancers. Selecting inertial balancer parameters to satisfy $J_M/J_P = (R/P)^2 + 2(R/P)$ in (a), (b) eliminates inherent coupling of body motion $\ddot{\theta}_b$ from the host vehicle into the LOS.

$$
\dot{\theta}_L(s) = \frac{G_c/J''}{s + G_c G_g/J''}\,\dot{\theta}_{\rm in}(s) - \frac{J_M/2J''}{s + G_c G_g/J''}\,\ddot{\theta}_b(s) + \frac{1/J''}{s + G_c G_g/J''} T_D\,, \tag{18}
$$

where $J'' = (J_M + 4J_g)/2$ and $T_D = 2T_{dg} + T_{dm}$. This equation compares functionally with (10) for the gear-driven mass-stabilized system. Although the specific parameter values are different, the same general conclusions hold. Specifically, the LOS is determined by a rate-command input signal, torque disturbances, and an inherent coupling of the host vehicle motion. This unavoidable coupling, which is not present in a mass-stabilized system, tends to drag along the LOS. Just like the gear-driven mass-stabilized system, this additional factor must be compensated by the control system.

Mirror Stabilization Using an Inertial Balancer

Although the stabilized mirror assembly couples host vehicle motions into the LOS, design refinements can reduce this effect. One such refinement is an *inertial balancer*, which consists of adding one or more rotating shafts onto the steel band that connects the mirror and gyro shafts. Figure 9(a) shows a free-body diagram for this arrangement; note that the inertial balancer shaft rotates opposite to the mirror and gyro shafts. Although the relationship between the mirror and gyro shaft is maintained at 2:1, the inertia and radius of the additional shaft is left to the designer. As in the case of the stabilized mirror, the choice of which shaft is connected to the motor is left to practical considerations; in fact, the motor can be mounted on the inertial balancer shaft. Assuming the motor is on the mirror shaft,

$$
J_M \frac{d^2\theta_M}{dt^2} = T_M - R(F_1 - F_3) + T_{dm}\,, \tag{19}
$$

$$
J_g \frac{d^2\theta_g}{dt^2} = r(F_2 - F_3) + T_{dg}\,, \tag{20}
$$

$$
J_P \frac{d^2\theta_P}{dt^2} = -P(F_1 - F_2) - T_{dP}\,. \tag{21}
$$

The additional equation (21) accounts for rotation angle θ_P of the inertial balancer shaft, where the inertia of the balancer shaft is J_P, the radius of the balancer shaft is P, and the coupling forces are represented by F_1, F_2, and F_3. The external disturbances (T_{dm}, T_{dg}, T_{dp}) applied to the shafts are modeled as disturbance torque terms. The kinematic relationships are given by

$$
\theta_g = \theta_{g/b} + \theta_b\,, \tag{22}
$$

$$
\theta_M = \theta_{M/b} + \theta_b\,, \tag{23}
$$

$$
\theta_p = \theta_{p/b} + \theta_b\,, \tag{24}
$$

$$
\theta_{g/b} = 2\theta_{M/b}\,, \tag{25}
$$

$$
\theta_{p/b} = -(R/P)\theta_{M/b}\,. \tag{26}
$$

As in the mirror-stabilization configuration, the 2:1 assembly is designed so that the gyro shaft moves in the

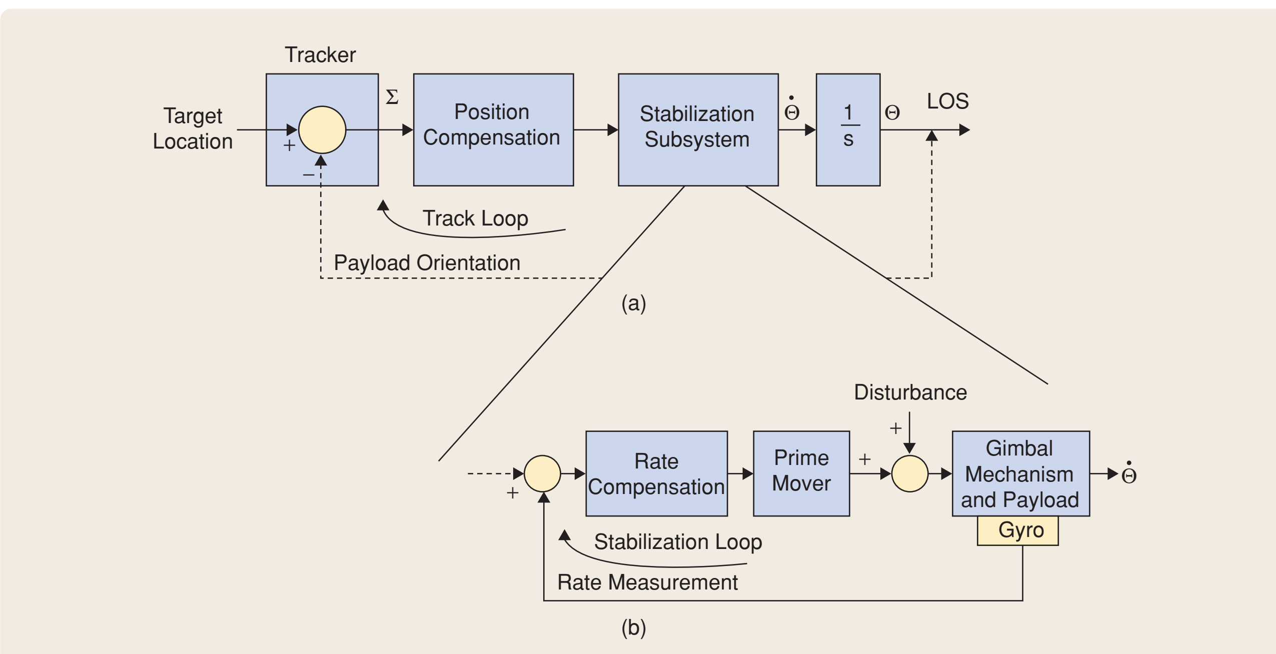

FIGURE 10 Control systems for inertially stabilized platforms. Typical control configurations for ISPs use (a) outer tracking loops and (b) inner stabilization loops. The tracker maintains the line of sight (LOS) oriented toward the target, while the gyro enables the stabilization loop to isolate LOS disturbances.

same manner as the LOS; hence, (16) holds. Manipulating (19)–(26) yields the LOS rate, which can be incorporated into the fundamental control loop in Figure 9(b) and solved to obtain

$$\dot{\theta}_L(s) = \frac{G_c/J_e}{s+G_cG_g/J_e}\,\dot{\theta}_{\text{in}}(s) + \frac{1/J_e}{s+G_cG_g/J_e}T_D + \frac{([(R/P)^2+2R/P]J_P - J_M)/2J_e}{s+G_cG_g/J_e}\,\ddot{\theta}_b(s)\,, \quad (27)$$

where $J_e = (J_M + 4J_g + (R/P)^2 J_P)/2$ and $T_D = 2T_{dg} + T_{dm} + 2rT_{dp}/P$. Although (27) is similar to (18), the numerator of the host vehicle coupling term contains a crucial minus sign; appropriate selection of the inertia and radius of the inertial balancer shaft can make this term zero. The inertial balancer parameters yielding this special condition are

$$J_M/J_P = (R/P)^2 + 2(R/P)\,. \quad (28)$$

Consequently, it is possible to design a mirror system that possesses the same characteristics as mass-stabilized systems, that is, with no inherent coupling of base motion.

However, additional considerations are necessary. For example, inclusion of the extra shaft in the coupling band introduces another source of friction that must be included in the torque disturbances T_{dp}. Furthermore, manufacturing tolerances must be examined to ascertain how accurately (28) can be satisfied. In addition, this approach may be more complex to design, assemble, and maintain. Nevertheless, with appropriate design tradeoffs, the stabilized mirror along with the inertial balancer can achieve high-precision operation.

Summary of Electromechanical Assemblies

As discussed above, an ISP electromechanical assembly may have a variety of physical configurations for controlling LOS. Each option has advantages and disadvantages. Mass-stabilized mechanisms typically provide superior performance compared to other configurations. Mirror mechanisms usually enable an optical system to be outfitted to a vehicle with less disruption to aerodynamic characteristics because the external protrusion may not be much larger than the mirror. The small cross section of a mirror assembly also makes it easier to protect an optical system in battlefield applications since the imaging sensor can be installed inside protective armor with only the mirror mechanism exposed.

Control Systems

Although design details vary, mass and mirror stabilization encompass a large variety of successful mechanical implementations; in practice, it is not uncommon for an ISP to use a combination of mass and mirror stabilization. We now examine how such mechanisms may be controlled.

The second ISP component is the control system, which ultimately determines the performance of the electromechanical assemblies. The control system has at least three functions, namely, stabilizing the sensor LOS to produce a high quality image, that is, minimizing image jitter; tracking to maintain the target within the sensor FOV; and measuring LOS orientation so that the location of the target can be determined in an appropriate coordinate system.

Most ISP control systems use an inner *rate* or *stabilization loop* inside an outer *track loop* as illustrated in Figure 10. The inner stabilization loop compensates for disturbances and minimizes unnecessary motion of the electromechanical assemblies. Meanwhile, the outer track loop ensures that the sensor LOS remains pointed toward the target.

Stabilization Loop

The inner-loop stabilization subsystem, illustrated in the lower portion of Figure 10, is a relatively high-bandwidth negative-feedback control system. The LOS rate, measured by the gyro, is summed with rate commands from the track loop and converted into drive commands by the rate-compensation/ actuator subsystem. The torque command generated by the actuator thus drives the mechanical assembly so that the LOS rate measured by the gyro is canceled and the LOS is held steady with minimal jitter. The rate-compensation electronics ensure closed-loop stability and tailor the overall servo characteristics of the stabilization loop.

TABLE 1. Classical Compensation Choices for a Stabilization Loop.

Compensation Type	Ease of Design	Command Responsiveness	Disturbance Rejection
Proportional (P) controller	Easy to design	Acceptable	Proportional controller low-frequency rejection is inferior to other types
Proportional-integral (PI) controller	Harder to design	Acceptable	PI low-frequency rejection is intermediate to other types
Proportional-integral-derivative (PID) controller	Hardest to design	Acceptable, but tends to oscillate	PID has the best low-frequency disturbance rejection

The fundamental elements of the stabilization loop are the actuator, gyro, and loop compensation. Actuators may be dc motors, ac motors, hydraulics, or pneumatic actuators. A variety of gyros are also available, including rate gyros, rate-integrating gyros, dynamic tuned gyros, multisensors, ring laser gyros, and fiber optic gyros.

When designing compensation for the stabilization loop, several characteristics must be addressed. Obviously, the loop must be stable, the mechanism must be responsive to track commands, and the loop must compensate for LOS disturbances. Table 1 summarizes several classical compensators frequently used for the stabilization control loop.

Since the fundamental purpose of the rate loop is to compensate for LOS disturbances, it is not surprising that disturbance rejection receives the most attention from ISP designers. Figure 11 illustrates normalized rejection responses for the three classical controllers frequently used for ISPs. At high frequencies, beyond the bandwidth of the controllers, all of the controllers display the inherent inertial characteristics of a gimbal mechanism. However, low frequencies within the bandwidth of the controllers display marked differences.

Proportional (P) controllers generally fail to provide adequate low-frequency disturbance rejection. As a result, proportional-integral (PI) and proportional-integral-derivative (PID) are much more prevalent. Although PID compensation usually provides the best low-frequency disturbance rejection, PID controllers are more prone to oscillation when command inputs are applied. In addition, an acceptably stable design is often harder to achieve with a PID controller when practical considerations, such as mechanical resonances, are considered.

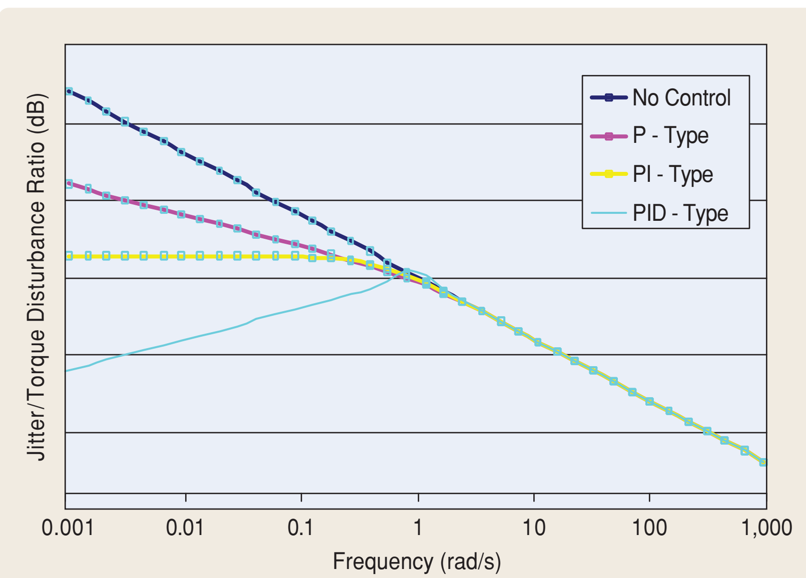

FIGURE 11 Line-of-sight (LOS) jitter-to-torque disturbance transfer function. Suppressing LOS motion (jitter) in response to torque disturbances, that is, disturbance rejection, is a critical performance metric for ISPs. PID-stabilization loop controllers provide better rejection of low-frequency disturbances than P or PI controllers.

Classical PI and PID compensators are usually adequate for a large class of high-precision stabilization loops. However, alternative compensators may be selected depending on the application and required accuracy. For example, friction compensation in addition to a more or less conventional controller may be necessary. Disturbance accommodating control [7] is also sometimes used. Alternative approaches have also been examined, including feedforward methods [8].

The physical implementation of the inner loop controller may be digital if digital signal processors have sufficient bandwidth for the particular application.

Track Loop

The track loop, also illustrated in Figure 10, is similar to the stabilization loop, but, unlike the inner loop, which operates on LOS rate, the track loop operates on LOS angle. Like the stabilization loop, the track loop must be stable, responsive to command inputs, and insensitive to disturbances and noise. Whereas the inner stabilization loop accepts commands from the track loop, the outer track loop accepts commands from the target tracker. The target tracker and the track loop must therefore be designed as an integrated process.

The target tracker processes optical imagery to determine target location within the sensor FOV. The tracker therefore measures relative target location with respect to sensor orientation, that is, the error between LOS orientation and target location. Image processing within the target tracker introduces computational delays that cause phase lag within the track loop. In addition to data latency, the tracker sometimes produces no information, such as when the target is obstructed from view. Nevertheless, target trackers with specialized signal processing techniques are available. The processes typically used in trackers are discussed in "Target Trackers."

The tracker is not perfect since it can produce both constant offset errors and random noise. Variations in video characteristics between successive samples of the image, when processed by the tracker algorithms, can generate jitter in the tracker output. In addition, for low signal-to-noise ratio imagery, a tracker may simply fail to measure target location for every video image, thus resulting in missing samples. In every case, the tracker is a sampled device, which provides output only at a fixed sample frequency, thus producing inevitable delays in the track loop.

Rate aiding is a process that can minimize tracker sampling limitations [15]. In rate aiding, a mathematical model of the target is used to estimate the target location. This model is updated by the sampled outputs from the tracker to estimate the target location between sample periods of tracker output. In the final step, the target model is extrapolated to predict target location. This prediction can also be used to calculate the required gimbal rates needed to track the target. These analytically derived gimbal rates can then be used as supplemental inputs to the stabilization/rate loop. In this manner, the gimbal rates become *rate-aiding* input commands for the stabilization loop. The process has inherent filtering to reduce tracker noise and interpolation for missing samples. Furthermore, if sufficient computation power is available, the mathematical model can provide estimates of target location at higher rates than those inherent in the fundamental target tracker.

Target Trackers

The most common target trackers are contrast edge, contrast centroid, adaptive gate centroid (AGCT), correlation, exceedance integration, histogram projection, extended Kalman trackers, and multimode [9]–[15]. The specific tracker choice for a given application depends on the intended target and its anticipated dynamics, the expected illumination (daylight or night), and whether or not fog, dust, smoke, or rain are present. Some target trackers are best for high contrast targets, some are best for moving targets, and some only work with targets that span several pixels within the sensor's optical image. Some trackers use adaptive algorithms that match the methodology with the application or operating conditions. Some, such as rate-aiding trackers, use supplementary information to improve tracking accuracy.

Although a human operator with a joystick and display can provide control commands to an ISP, most target trackers are automatic, in which video imagery is processed to estimate target location. Automatic target trackers typically require a target recognition process, or manual operator, to initially *designate*, or acquire, the target. The tracking process thus begins when the tracker is informed that a selected portion of a video image represents a target. The tracker processes the selected video to evaluate the target signature and determine whether the tracker algorithm can detect unique characteristics that enable the tracker to continue operation. If the signature is adequate for the algorithms, the tracker acquires the target and begins tracking. In the most basic operation, the tracker estimates the position of the target in each sequential image generated by the payload. Advanced target trackers continually monitor the target's *signature* from frame to frame to determine whether tracking is likely to continue, and most advanced trackers provide a measure of confidence for overall tracking quality.

Numerous types of trackers based on varying operating principles are available. Generally, the best choice for any given scenario depends on factors such as expected target size, target shape, signal-to-noise ratio, and clutter (background noise) characteristics. Tracker operations are generally defined in terms of five specific functions; Figure S1 illustrates the interactions among these functions.

Data processing preprocesses the imagery in each video sequence to improve efficiency. For example, in some trackers, analog video is converted to binary data by comparing each pixel to a preset threshold. Such operations significantly reduce the complexity of the video.

Gate sizing identifies or selects the specific sub-regions within the overall video sequence in which the tracker algorithm operates.

Algorithm operation, or tracking, estimates target location within the gate of consideration. An algorithm can use contrast of the various pixels, pattern correlation, or other criteria as the basis for identifying which pixels correspond to the target. The fundamental output of the tracker is the vertical and horizontal positions within the video estimated to correspond to the target. That is, the tracker identifies the *horizontal* and *vertical* locations of the target within each video sequence frame.

Fault detection determines and measures the operating state of the tracker. This operation thus provides a measure of the confidence of the target location computed by the algorithm.

Control maintains top-level operation of the tracker in response to operator inputs and fault detection measurements to ensure continuous target lock-on. In the event a given video sequence is unable to yield a confident estimate of target location, actions can commence to reacquire the target. Provisions can also be incorporated to enable the tracker to *coast* during a series of video frames when the target is temporarily obscured from view.

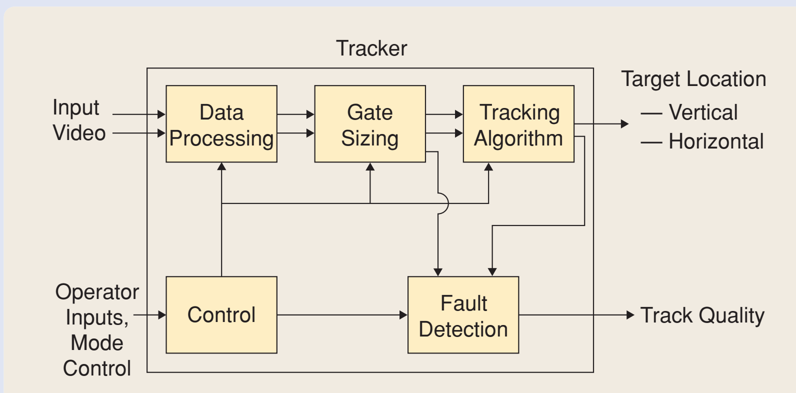

FIGURE S1 Target tracker functions. Target trackers process video imagery to determine two-dimensional target location within the sensor field of view. The tracker also determines a confidence measure, or track quality measure, for the calculated target location.

Auxiliary Equipment

In addition to electromechanical assemblies, gyros, target trackers, and the stabilization and tracking control loops, various auxiliary components are needed in a practical ISP. *Position sensors* measure gimbal rotations, which are then transformed into LOS orientation. These measurements are essential if the location of a target is to be handed off to another system. In the reverse situation, if a specific target location measured by another system is to be located and acquired by the host sensor, then measurements of the LOS are needed as feedback when moving to the prescribed orientation. Position-measurement devices include potentiometers, resolvers, encoders, and synchros.

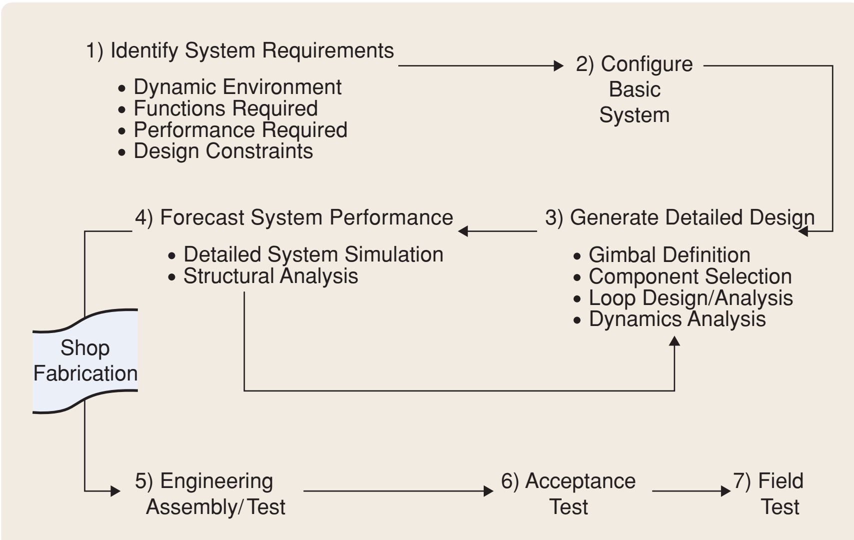

FIGURE 12 Inertially stabilized platform design and development process. The design and development of an ISP is a multi-tasked system engineering process, which requires numerous design disciplines, careful design procedures, frequent tradeoffs, and a systematic approach.

INSs or IMUs provide inertial references, which are used to generate LOS orientation with respect to both inertial space and the host vehicle.

Rotary joints are frequently employed when fluids or gases must be transferred from the host vehicle to the payload. If the total available gimbal rotation is small, flexible hoses may be used rather than rotary joints.

Electrical slip-ring assemblies provide electrical interface between the host vehicle and sensor payloads if unlimited or wide rotation is anticipated. However, if the total gimbal rotations are modest, then long electrical cables or *surface loops* across gimbal axes are usually sufficient.

Mechanical bearings are fundamental to the electromechanical assemblies; these components impact the precision

Design Guidelines

Development of an ISP for an imaging sensor is a multidisciplinary process that depends on the specific application and the operating environment. Nevertheless, some general guidelines can be defined. A state-of-the-art ISP typically achieves LOS jitter levels within the microradian range. The guidelines are essential for such precise performance.

As a general guideline, although discussing stabilization and tracking as *separate* functions is convenient, they are not independent. Tradeoffs are inevitable between stabilization, which seeks to hold everything *fixed* in inertial space, and tracking, which seeks to *change* the LOS orientation to follow target maneuvers. A designer must remain vigilant since design changes that improve one function can adversely affect another. In addition, an ISP and payload must fit and function as an integral part of an overall system to be installed into a host vehicle. The ISP must not adversely affect the host vehicle, the user of the system, or auxiliary equipment.

Although described as the first step in the development, one cannot overemphasize that requirements and design budgets must be established early in the design process. As a minimum, requirements must define system weight, size, power consumption, torque requirements for actuators, and total angular travel for the LOS. Up-to-date estimates and design budgets should be maintained for all design parameters throughout the development process. Budgets for stabilization jitter and tracking error are obviously critical for an ISP.

A designer must carefully define the operating environment and its impact on the ISP. Factors to be considered include operating temperature range, expected temperature gradients, vibration levels, and mechanical shock. These factors affect fundamental decisions such as the need to cool actuators and electronic drivers.

When packaging constraints permit, *mass stabilization* should be used to the greatest degree possible. The inherent self-stabilization tendencies of mass stabilization provide a clear advantage. The unavoidable coupling of base motion into gear-driven or mirror configurations require special design efforts, especially for applications where the host vehicle has significant rotary vibration.

Gimbal assembly *balance* is essential, and if not achieved by the fundamental layout of the system, then balance weights must be added. Attention should be given during system design to allow provision for subsequent addition and adjustment of the weights, as well as minimizing their number since they are nonfunctional weight. In an ideal design, the centerline of rotation for each gimbal passes through the ISP center of gravity.

and smoothness with which LOS motion is achieved. Unfortunately, in most applications, friction is a major disturbance, and bearings and seals on the gimbal assemblies are typically the major contributor to friction levels.

DESIGN METHODOLOGY AND GUIDELINES

Design and development of an ISP is a multidisciplinary, multistep process that begins with a precise definition of requirements and a clear understanding of operating environments, followed by detailed design tradeoffs, careful fabrication, system integration, and testing.

Development Process

Although a variety of electromechanical mechanisms can be used and various stabilization/tracking compensators can be selected, the development process is fundamentally the same for all systems. Figure 12 presents a typical flow of this process.

Step 1: Identify System Requirements

Formal definition of system requirements is probably the most critical step in the overall process and may be the most difficult. Top-level system performance requirements are usually generated by analyzing the overall *functions* to be achieved, the *mission scenario*, and the *type of payload* to be used. The overall function of a system may be to collect imagery for surveillance, target tracking, fire control, or simple pointing or scanning within a selected geographic location. Each of these applications imposes different ISP requirements due to their unique objectives and operating environments. For example, long-range surveillance applications require precise pointing and ultra-fine stabilization, but may operate in a relatively benign environment. On the other hand, fire control applications with shorter operating ranges typically have more modest accuracy requirements, but almost certainly have severe operating environments.

Careful analysis of system functions, mission scenarios, and payload type eventually yields a list of ISP requirements including design constraints, operating dynamics, and performance goals. Design constraints include allowable size, weight, power consumption, and cost targets for the ISP. Performance goals identify the precision with which mechanical motion must be measured and controlled. Dynamic requirements include characteristics such as bandwidth or frequency response-step response.

Step 2: Configure Basic System

After the system requirements and constraints are defined and translated into parameters suitable for specification of the ISP, basic design decisions are made. At this point, several candidate design concepts are typically considered. Choices are made between mass stabilization and mirror stabilization. Potential actuators are selected to drive the stabilization mechanisms, and preliminary choices are made for the gyro, position pickoffs, and other ISP components. Tentative configurations for the servo loops are defined.

Since gyros provide the fundamental measurement of LOS, they must be arranged and aligned for optimal accuracy and maximum sensitivity. Ideally, gyros should be located so that their input axes always remain orthogonal to the payload LOS. However, this goal is sometimes impossible to realize, especially for mirror-stabilized mechanisms. Performance is generally degraded in such arrangements. "Where Do You Put the Gyros?" examines alternative gyro locations for mirror-stabilized systems.

Some payloads contain internal coolers and scanner mechanisms that produce linear vibration forces. To minimize disturbance torques, such internal vibrating elements must be positioned within the package so that the vibration forces pass through rotation centerlines. Likewise, internal components that produce torsional vibration should be located so that the resultant torque is not about an axis of rotation for a gimbal.

Mechanical focus mechanisms, lens-switching assemblies, and zoom lenses produce center of gravity shifts that can upset system balance, thus introducing the potential for a torque disturbance. For systems with multiple FOVs, it is best to balance the system when it is in the smallest FOV since this mode of operation is most sensitive to disturbances from center of gravity shifts. In some cases, moving counterweights can be designed to maintain center of gravity even when operating adjustments are made. However, such designs add weight to the system.

Material properties must be considered during design. Thermal coefficients must be matched or design provisions must be included to accommodate mismatch in materials since operating temperatures inevitably change during operation. Furthermore, many payloads have internal heating or cooling, which produces large thermal gradients within a payload. Thermal gradients can disturb alignment of optics which may introduce LOS error. The stiffness and strength of materials chosen for an ISP and a payload also need to be considered. Flexure of a package may produce misalignments or high-frequency internal jitter. Material and fabrication cost is another critical factor to be considered during design. Some materials are not particularly expensive to purchase in raw stock but may be costly to machine or process.

The designer must plan ahead for ease of adjustments, alignment provisions, and system testing. Adequate electrical access points are useful to facilitate system troubleshooting. Attention must also be given to assembly methods to ensure that the ISP and payload can be disassembled, re-assembled, and maintained in the field. Reliability should be designed into the system.

Step 3: Generate Detailed Design

After the basic mechanical configuration is tentatively defined, attention turns to details that yield a complete design suitable for hardware fabrication. In this step, the mechanisms are finalized, and detailed drawings are generated. The drawings are used for detailed structural analysis and predictions of weight, strength, and production cost. Final choices are made for purchased components including actuators, pickoffs, and gyros. The control-loop designs are finished, including compensation techniques required to ensure stability and dynamic response characteristics. Electronics and interfaces to other systems are defined.

Step 4: Forecast System Performance

Although the design may be complete, it is considered tentative until it is sufficiently examined to yield reasonable confidence that the ISP satisfies all requirements [17], [18]. System simulation is the key tool for such examinations. Mathematical models for the gimbals are based on fundamental relationships between torque and angular acceleration, where estimates of the moments of inertia are based on engineering drawings. Detailed finite-element models are generated to estimate structural interactions and mechanical resonances. Adequate simulation models of purchased components (actuators, gyros, bearings, electronics) are usually available from manufacturers. Operating disturbances (friction, wind, vehicle motion, vibration, motor cogging, electronic noise, imbalance) are all modeled as equivalent torque disturbances. Bearing friction is estimated from analysis of the mechanical preload levels to be used in the bearings.

The feedback between steps 3 and 4 shown in Figure 12 illustrates the iterative process in which performance is forecast, the design is tweaked, and then performance is again reforecast and repeated, as necessary.

After a suitable design is achieved, it is released for fabrication, components are purchased, and electronic assemblies are constructed. In the meantime, the payload sensor is designed and fabricated.

Where Do You Put the Gyros?

Gyros are the key sensors for stabilization. The purpose of the stabilization control loop is to null the gyro measurements and thereby minimize LOS jitter. Obviously the *input axes* of the gyros must be mechanically aligned within the ISP so that the gyros accurately measure LOS motion.

Two axes of LOS must be measured by the gyros. Consider a Cartesian x-y-z coordinate frame. If the x-axis is LOS, the ISP must minimize inertial rotation around the y- and z- axes. Gyros must therefore be installed to measure rotation around both the y- and z- axes. A dual-axis gyro, which simultaneously measures rotation around two orthogonal axes, can sometimes be installed so that the input axes are always aligned with the y- and z- axes.

Alignment of the gyro input axes with the LOS is straightforward in a mass-stabilized ISP. Since the LOS is controlled by moving the entire payload, a fixed installation of the gyros within the ISP ensures the gyros are always aligned to measure both y- and z-axis motions. A dual-axis gyro therefore works fine in a mass-stabilized ISP.

However, in a mirror-stabilized ISP, the best location for the gyros is not immediately obvious. The steering mirror is the movable element in the ISP, but the mirror and LOS orientation do not always align. Optical doubling, as discussed earlier, rotates the LOS by an amount that is double the rotation of the steering mirror. Since the goal is to control LOS, we must therefore stabilize LOS rather than the mirror. At least three approaches for installing gyros within a mirror-stabilized mechanism are feasible; namely, on an auxiliary axis, on the mirror, or in the host vehicle close to the ISP.

AUXILIARY AXIS

The most common and most accurate approach for a precision ISP is to add an auxiliary shaft on which to install the gyros. Figure 7 illustrates this approach. The auxiliary shaft is designed so that rotation in the plane where optical doubling occurs is always double the steering mirror rotation. Gyros mounted on the auxiliary axis, like gyros in a mass-stabilized mechanism, are thus always aligned to directly measure both the y- and z- components of LOS wherever the LOS may be oriented. A dual-axis gyro therefore works fine. The 2:1 ratio for the auxiliary and mirror shafts must be carefully designed, and flexible steel bands are typically used for the coupling. The bands are installed so they remain in tension over a wide range of operating temperatures, mechanical shock, and vibration. Rigid linkages may also be used to couple the mirror and auxiliary shafts.

A variation of the mechanical linkage or band configuration is to fabricate a stand alone auxiliary shaft without direct physical coupling, but driven by an active servo. A precision resolver measures mirror rotation, and the servo uses the measurement to drive the auxiliary shaft so that it rotates twice the rotation of the mirror. Although either a direct mechanical linkage or a servo-driven auxiliary shaft can be used, the critical requirement is that the input axes of both gyros, installed on the auxiliary shaft, are always aligned with the LOS wherever the LOS may be oriented.

When using an auxiliary shaft, the stabilization control loop always drives the gyros to null. That is, LOS is stabilized when the ISP is controlled so that the gyro measurements approach zero. Since the gyros operate near null, the only critical gyro specifications become low noise and adequate bandwidth. Scale-factor accuracy, linearity, dynamic range, and all other gyro errors related to non-null operation are not critical because the gyros always operate near null when the LOS is stabilized. This reduction in the number of critical gyro specifications enables gyro manufacturers to optimize performance and reduce gyro cost.

MIRROR-MOUNTED GYROS

To eliminate the auxiliary shaft, the gyros can be installed directly on the mirror. However, since the mirror's orientation is not the same as

Step 5: Engineering Assembly and Testing

After the mechanisms are fabricated, purchased components are received, and the electronics are constructed, a working ISP prototype is assembled. A dummy payload with the same form factor and inertia characteristics as the optical sensor is typically used during initial integration and testing. This substitution allows the ISP design team to conduct characterization tests and make modifications, if necessary, without tying up the design engineers who are concerned with the optical sensor. When subsystem tests are completed on both the ISP and the optical sensor, the overall system is then integrated and tested. Some of the test equipment may be quite sophisticated. For example, motion simulation and vibration tables are typically used to subject the ISP and the optical sensor to environmental stresses, while elaborate optical benches are used to assess the optical performance of the payload.

Step 6: Acceptance and Field Tests

In the final steps, the full system is integrated, and an *acceptance test* of the stand-alone system is conducted prior to field tests in which the ISP and optical payload are installed in the host vehicle.

Guidelines

Development of an ISP and its payload usually follows the above methodology. However, design details are unique for each application. Nevertheless, "Design Guidelines" offers suggestions that are useful in many situations.

STATE-OF-THE-ART PERFORMANCE

Using an ISP to control LOS is not a new application. However, the accuracy of LOS control has progressively improved, and the precision of a modern ISP is truly impressive. The ultimate performance criteria are quality, clarity, and sharpness of images produced by the optical sensor despite host vehicle and target motion. Since LOS jitter degrades image

LOS orientation, gyros mounted on the mirror do not directly measure LOS motion. As the mirror rotates, the input axes of the gyros, fixed to the mirror, rotate relative to the LOS x-y-z triad. Nevertheless, LOS orientation can be reconstructed if additional measurements are available [19]. For the axis in which optical doubling occurs, simply doubling the gyro's rate measurement effectively reconstructs this component of LOS rate. However, the input axis of the second gyro, mounted on the rotating mirror, tilts out of alignment with its desired LOS measurement as the mirror rotates. This loss of measurement sensitivity can be compensated by adding a third gyro, whose input axis is orthogonal to the other two gyros, and then combining appropriate components of the second and third gyro measurements. The appropriate component from the second and third gyro clearly depends on the amount of mirror rotation, so a resolver is needed to measure mirror rotation.

Thus, if gyros are to be mounted directly on the mirror, we must add a third gyro and a resolver to measure mirror rotation. Appropriately combining these measurements reconstructs the LOS rate, which can then be used to stabilize LOS. Obviously, noise characteristics and accuracy of the resolver are critical. In addition, since the gyros are not aligned with the LOS, they do not always operate around null. Precise measurement of nonzero rate is therefore necessary, therefore gyro scale-factor error, linearity, and dynamic range become important, as well as noise and precision in the processing electronics that perform the LOS reconstruction.

BASE-MOUNTED GYROS

Finally, the gyros can be installed directly in the host vehicle in the vicinity of the ISP base. As in the case of gyros mounted on the mirror, the orientation of the base is not the same as the x-y-z orientation of the LOS. However, if three orthogonal gyros are mounted on the base and if the mirror and other gimbal rotations are measured, then the gyro signals can be processed by a sequence of Euler transformations to reconstruct LOS measurements in the x-y-z coordinate axes. If either of the y- and z- measurements is nonzero, then appropriate drive signals can be processed back through the Euler transformations to generate commands for the mirror and the remaining axes of the ISP. As shown in [19], the hardware requirements include three gyros and precision resolvers to measure the mirror orientation relative to the base.

Many vehicles with optical sensor payloads carry IMUs for navigation and vehicle control functions. Sometimes, it is possible to use the IMU measurements in place of the three gyros mounted on the base. However, in most cases, the IMU is installed remotely from the ISP so that the IMU measurements are not precisely the same as the host vehicle dynamics in the vicinity of the ISP. Furthermore, an IMU designed for navigation is optimized for low drift, as required for navigation, rather than for the high bandwidth, low noise measurements needed for stabilization. As in the case of mirror-mounted gyros, the gyros in the IMU do not operate at null, and thus scale-factor, linearity, and dynamic-range errors within the gyros also hamper reconstruction accuracy.

The overall packaging constraints of an ISP application can significantly impact the available design choices. In general, a mirror-stabilized ISP, using an auxiliary shaft, requires less volume than a mass-stabilized mechanism. If space is further limited, a mirror configuration with gyros mounted directly on the mirror or on the vehicle near the ISP may be the only option. However, LOS reconstruction processes for an ISP without an auxiliary shaft require advanced gimbal-position resolvers, while the demands on linearity, scale-factor, and dynamic range for the gyros are much more severe.

quality, jitter reduction is commonly cited as a suitable performance measure for ISP performance. Thirty years ago, a state-of-the-art ISP reduced LOS jitter for optical sensors installed on land- or sea-based vehicles down to hundreds of microradians. Precise ISPs today reduce jitter to less than 10 μrad even for vehicles with highly dynamic motion (high-speed, heavily armored vehicles traversing off-road terrain, high agility helicopters, and maneuvering ships on high sea-states). ISPs operating in more benign environments, such as in space vehicles, reduce LOS jitter to even lower levels.

Impressive improvements in ISP performance are the result of several advancements. Increasing operational bandwidth directly translates into improved disturbance rejection, while improvements in gyros, actuators, and electronics enable new controllers to be implemented with increased bandwidth. Modern mechanical designs, along with new materials, yield better balanced, stronger, and stiffer mechanisms. Stiffer mechanisms have higher mechanical resonance frequencies, which permit higher bandwidth. ISP jitter is also minimized by noise reduction in gyros, actuators, and electronics.

No doubt one of the key motivations for improving ISP performance is a genuine need for such improvements. Optical imaging sensor performance and resolution have dramatically improved in recent years. However, since an ISP provides the critical role of stabilizing the sensor LOS, the value of increased sensor resolution cannot be fully realized unless corresponding improvements in LOS stabilization accompany the sensor advancements.

CONCLUSIONS

Control of LOS orientation is a fundamental prerequisite for virtually all dynamic applications in which an optical sensor is used to collect information or obtain images. If an optical sensor is not properly oriented or if the imagery of the sensor is degraded, the sensor information is not useful. When the imaging sensor is carried on a mobile vehicle, or for any application in which a dynamic target is to be observed, an ISP is essential.

The fundamental elements of ISPs used to control imaging sensors are electromechanical assemblies, control loops with gyros and trackers as feedback sensors, and auxiliary equipment. Design of stabilization-tracking systems is a multidisciplinary, multistep process, which commences with precise definitions of requirements and a clear understanding of operating environments, followed by detailed design tradeoffs, careful fabrication, system integration, and test.

DEDICATION

This article is dedicated to the memory of Dr. Larry A. Stockum, a talented, intelligent, and devoted engineer who understood all of the diverse technologies involved in design, fabrication, testing, and application of ISPs. Even more important, Larry Stockum was a kind, gentle, and most optimistic friend. He passed away on August 9, 2006.

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