GYROSCOPES

A gyroscope, sometimes called a *gyro,* is conventionally a rigid body or wheel, spinning around an axis of rotation mounted in a movable frame. This movable frame permits the spinning wheel to tilt freely in any direction and rotate about any axis (Fig. 1).

One of the basic modes of operation and functionality of such a gyroscope can be understood by considering an airplane in which the gyroscope is mounted. In this mode of operation, the gyroscope is used as an instrument that measures the tilt and orientation of the plane. Associated with any spinning object is a quantity known as the *angular mo-*

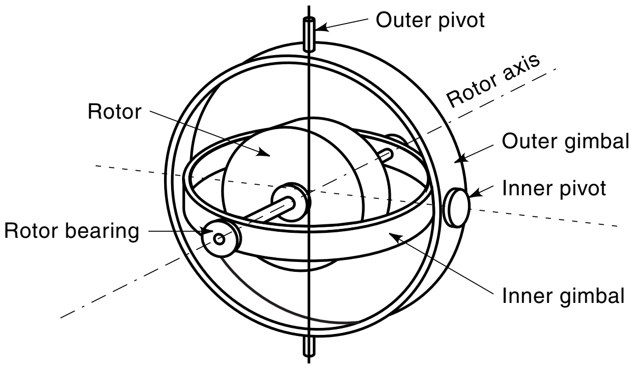

Figure 1. Parts of a two-axis flywheel gyroscope. The rigid body or wheel is referred to as the *rotor.* The two rings are referred to as *gimbals,* and constitute the movable frame.

mentum. The angular momentum is the product of the spinning body's *angular velocity* and *rotational inertia.* The angular velocity is measured in radians per second. The rotational inertia, also known as the moment of inertia, depends on the mass and geometry of the body. Conservation of angular momentum is one of the basic principles of classical mechanics. According to this principle, any body upon which no net external torque is applied maintains its angular momentum. For a rigid body under appropriate conditions, this means not only that the angular velocity remains constant, but also that the axis of rotation does not change. The function of the movable frame is to suspend the rotor in such a way that no external net torque acts on it. Thus, if the airplane changes its orientation by tilting in one or more possible ways, the rotor will nevertheless keep spinning with the same velocity and with its axis pointing in the same direction. The frame, which is secured to the body of the airplane, will move around the rotor freely. By measuring this motion, it is possible to determine how much the plane has tilted with respect to its original orientation.

One of the most familiar example of a gyroscope is a toy spinning top. Such toy tops are usually set in motion by wrapping a string around the axle and pulling the string. They can perform amazing tricks such as balancing at an angle on the end of a finger or pencil even if the finger or pencil is moved randomly. If a spinning top is pushed gently in one direction, it seems to prefer another, and it moves obstinately in a direction perpendicular to the original force. As another familiar example of the gyroscopic principle in action, we might mention footballs and bullets, which are given a spin while setting them in motion, to keep them stable in flight and send them straight to the target. The same principles that govern the action of gyroscopes are also observed in nature. For example, the earth behaves as a giant gyroscope as it revolves around the sun.

Most modern gyroscopes can be broadly classified into two kinds:

- Mechanical gyroscopes
- Optical gyroscopes

Mechanical gyroscopes are based on the conservation of angular or linear momentum (1). The best-known example of a mechanical gyroscope is the *flywheel gyroscope* discussed above. Some more recent mechanical gyroscopes are based on vibrating, rather than rotating, structures. These vibrating structures are in the form of a tuning fork or a membrane or some other geometry.

Although optical gyroscopes do not contain rotating or vibrating masses, they serve the same purpose as mechanical gyroscopes. Optical gyroscopes have been under development as replacements for mechanical ones for over three decades. The operation of optical gyroscopes is often based on analyzing the interference pattern of two beams of light counterpropagating around a closed path. The interference pattern is an indicator of the direction of rotation. Having very few or no moving parts, these devices are easier to maintain. They also have no gravitational sensitivity, eliminating the need for gimbals.

Whether optical or mechanical in nature, gyroscopes can be further classified into two kinds as (1) *rate gyros,* which provide a voltage or frequency output signal proportional to the turning rate, and (2) *rate-integrating gyros,* which provide the actual turn angle (2). Fundamentally, gyroscopes provide angular rate information. It is important to note that rate-integrating gyros only detect relative angular position, and not absolute angular position like a magnetic compass. Thus, they must be initially referenced to a known orientation by some other means.

Although the rate information can be reliable over long periods of time, when integrated to provide orientation output, even very small rate errors can cause an unbounded growth in the error of integrated measurements. As a consequence, a gyroscope by itself is characterized by *drift* or position errors that grow with time. One way of overcoming this problem is to periodically reset the gyro output with other absolute location-sensing mechanisms and so eliminate the accumulated error.

Gyroscopes have a wide spectrum of applications. The most important use of gyroscopes is in navigation and stabilization instruments for aircraft, spacecraft, guided satellites, missiles, large ships, submarines and other underwater vehicles, cars and other land vehicles, and robots. Some of the specific gyroscopic instruments used are high-performance attitude and heading reference systems, compasses, stabilizers (anti-roll equipment), autopilots, and inertial navigation systems (INSs).

An attitude and heading reference system determines the tilts of the vehicle in different directions, so as to aid stabilization, maneuvering, and navigation. Many other gyroscopic instruments, such as the rate-of-turn indicators and the gyro horizons, help aircraft pilots know the position and motion of their plane in the air. Ordinary magnetic compasses are affected by magnetic forces caused by the rolling and pitching of a ship. Gyroscopes are used to regulate such compasses so that navigators know more accurately in what direction their craft are headed. Gyrostabilizers compensate for the rolling of ships at sea, helping restore them to an erect position. Autopilots guide vehicles towards a destination with minimum or no human intervention. The purpose of INSs is to provide position and attitude information.

Gyros find other applications in mining and surveying, the automotive industry, medicine, motion measurement systems, and pointing technology for computers.

Gyroscopes with different accuracies are demanded in different application areas. High-accuracy gyros are required for aircraft, ships, and land vehicles. Medium-accuracy gyros are suitable for less-demanding applications such as vehicles with short flight times (e.g. some missiles) and land navigation systems. Accuracy is often measured in degrees per hour (deg/h). An accuracy of 1 deg/h means that the system makes an angular drift error of one degree over one hour of operation (3). Medium accuracy is defined as a bearing drift in the range 0.1 to 1.0 deg/h; high accuracy, a drift less than 0.01 deg/h (4). For instance, a drift of 1 deg/h would be acceptable in a warhead seeker or flight control system, but would only be tolerable for a short time for standalone navigation.

The *scale factor* of a gyroscope is defined as the ratio of the desired angle or rate information to the physical output (e.g. a voltage or a frequency) of the gyro. The scale factor can be asymmetric for positive and negative rates in mechanical gyroscopes and can be a source of error. This is much less of a problem for certain optical gyroscopes.

Gyro bias is the deviation between the ideal output of the gyro and its actual output. *Gyro bias error* is defined as the difference between the true low-frequency gyro bias (with period greater than the mission time) and the calibrated gyro bias value loaded in the computer to compensate for this error. As long as this quantity remains stable and the calibrated value is subtracted from the gyro output, the compensated gyro output will be correct. One-year stability of this error to better than 0.004 deg/h is achievable (5).

Thermal gradients in the environment affect all types of gyros. Unless adequate error models are built and incorporated in the system model, such errors will also drift the output. Current systems are able to compensate for thermal drift so that the residual thermal drift rate remains under 0.004 deg/h over a wide range of temperatures (5).

Magnetic sensitivity to the earth's magnetic field or to fields created by other instrumentation nearby is another source of error. Proper shielding enables reduction of magnetic sensitivity by a factor of 60 (5).

HISTORY

The first written record of a gyroscope is found in Gilbert's Annalen of 1818. In that report, a flywheel gyroscope constructed in 1810 by a German scientist named G. C. Bohnenberger is described. Instead of a wheel at the center, it had a heavy rotor that was almost spherical, supported by three gimbals. The nineteenth-century French physicist J. B. L. Foucault first used the word gyroscope in 1852 to describe a device he had built to further confirm the rotation of the earth (6). Foucault had earlier demonstrated the rotation of the earth with the pendulum known by his name. However, his gyroscope failed due to the limited technical capabilities of his time. The device was basically a wheel, or rotor, mounted on a long axle within a framework composed of gimbal rings suspended on a ligament. The Foucault gyroscope with the framework suspended on a ligament is considered the original form of the north-seeking gyro. Foucault demonstrated that the spinning wheel maintained its original orientation in space regardless of the earth's rotation. He named this instrument a *gyroscope,* from the Greek words *gyros* (revolution) and *skopein* (to view). Thus, gyroscope means *to view a rotating body*.

A Scot, R. Whitehead, first used the gyroscope in military equipment by perfecting a gyroscopically controlled torpedo in 1896. Although the ability of a gyroscope to maintain its orientation suggested its use as a direction indicator, practical applications of the gyroscope were few before the twentieth century. This was because the equipment needed to keep the rotor of large gyroscopes spinning smoothly, such as electric motors and ball bearings, had not yet been developed. At that time, also, machining techniques were not sufficiently advanced to produce precision instruments.

About 1900, more ships were being built of steel instead of wood. The magnetic compasses that had been satisfactory in wooden ships were less reliable in steel hulls. To overcome this problem, the first gyrocompass for ships was invented and patented by a German scientist and engineer H. Anschütz-Kämpfe in 1903 (6). His colleague Schuler solved the problem of filtering external disturbing motions for the first time.

One of the leading figures in the development of the gyroscope was a US scientist and inventor, Elmer A. Sperry (1860–1930), who became interested in the instrument after seeing Foucault's historic gyroscope in France. In 1909, Sperry built the first automatic pilot using the direction-keeping properties of a gyroscope to keep an aircraft on route. In 1911, he successfully demonstrated a gyrocompass on a US battleship named Delaware. The same year, he patented and marketed a gyrocompass in the United States, and one was produced in Britain soon after. The Germany navy had also introduced gyrocompasses into its fleets by 1911. Sperry continued to extend the range of instruments based on the gyroscope.

The first autopilot for ships was produced by the Anschütz Company in Kiel, Germany, and installed in a Danish passenger ship in 1916. A three-frame gyroscope was used in the same year in the design of the first artificial horizon for aircraft. This instrument indicates roll (side to side) and pitch (fore and aft) attitude to the pilot and is especially useful in the absence of a visible horizon.

In 1912, Sperry's son Lawrence Sperry invented and flight-tested an automatic pilot that used four gyroscopes to stabilize an airplane. He competed with 53 others in a competition in Paris in 1914 and won a prize for the most stable airplane. In 1918, he developed the gyroscopically controlled turn indicator for airplanes.

The British fleet made use of a Sperry gyrocompass in World War I. The Sperry Gyroscope Company (now Sperry Marine, Inc.) devised a quite effective gyrostabilizer that reduced the rolling of ships in 1915. This not only minimized damage to cargo and increased passenger comfort, it also reduced stress in the hull of the ship. This gyrostabilizer fell out of favor because of its large weight, size, and cost. It was replaced by an underwater fin-type ship stabilizer developed by Japanese shipbuilders in 1925.

The directional gyroscope and the gyro horizon, which enable aircraft to fly safely at night and in bad weather, were developed by the Sperry Gyroscope Company in 1928. The same company developed its first gyropilot flight control for modern planes in 1932. This automatic pilot was installed on Wiley Post's airplane, the Winnie Mae. The automatic pilot helped Post make the first solo flight around the world in 1933 in a little more than 7 days, 18 hours. Sperry Gyroscope Company also led the development of several other gyroscopic instruments.

The principle of operation of the optical gyroscope was first discussed by Sagnac in 1913 (7). Sagnac's interferometer experiment produced a sensitivity of 2 rad/s. However, several technological developments had to be made before it could be put into practical use. Two years after the demonstration of the helium–neon laser at Bell Laboratories in 1960, the first operational ring-laser gyroscope (RLG) was developed by Warren Macek of Sperry Corporation (8). It took about two decades to achieve accuracies of 0.01 deg/h. In the early 1980s, smaller, lighter, more reliable RLGs quickly replaced the traditional spinning-wheel gyroscopes for applications such as commercial aircraft or automobile navigation. Navigational-quality RLGs (Fig. 2) have been employed in INSs for Boeing 757 and 767 airplanes since then.

As a result of the advances in the telecommunications industry, in particular optical fiber technology, fiber-optic gyroscopes (FOGs) have emerged as a low-cost alternative to

Figure 2. MK-49 ring laser gyro navigator by Sperry Marine Inc. This is a navigational quality gyroscope. (Photo courtesy of Sperry Marine Inc., Charlottesville, VA.)

RLGs (9). A FOG was first demonstrated by Stanford University researchers Vaili and Shorthill (10) in 1976. As with RLGs, it took about two decades to develop the technology in order to achieve better accuracies (11). More mature FOG technology emerged in the early 1990s. More than half a million navigation systems utilizing FOGs have been installed in Japanese automobiles since 1987 (12).

Mechanical Gyroscopes

Gyroscopic Forces. It is well known that spinning changes the properties of a body such as a cone-shaped toy top. For instance, while the top cannot stand on its pointed end when not spinning, it can easily be balanced on its pointed end when it is rapidly spinning. Why does the spinning motion give the system stability? Most simply, because the top is “confused” about which way to tip. If it starts to tip in one way, the rotation quickly reorients the tipping motion, and a new tipping process begins. The net result of this continuing process of tipping and reorientation is that the axis of the spinning top moves uniformly about a vertical line; this is the motion known as *precession.*

The operation of a bicycle depends on gyroscopic effects. The rider must control the gyroscopic forces in order to ride the bicycle successfully. To keep the bicycle standing upright, the wheels must be kept spinning. If the rider leans slightly to one side, the bicycle does not fall over, but turns in the same direction. Bicycles show two gyroscopic effects: (1) gyroscopic inertia, and (2) precession.

Gyroscopic inertia is the ability of the spinning axle of the gyroscope to maintain the same direction, no matter how the support of the gyroscope changes. The spin axis possesses inertia in the sense that it will maintain its direction as long as the gyroscope is undisturbed and continues to spin. The inertia of a body is its resistance to any change in its state of motion. Gyroscopic inertia plays an important role in determining a gyroscope’s behavior. It is gyroscopic inertia that keeps the bicycle upright as long as the wheels keep spinning. If the speed of the wheel decreases, the gyroscopic inertia gradually disappears; the axle begins to wobble and ultimately becomes unstable. Rotors with a high speed and a concentration of mass toward the rim of the wheel display the strongest gyroscopic inertia.

The consequence of gyroscopic inertia is that if a motor-driven gyroscope is observed for several days, its axis will appear to change its direction slowly, returning to its original position every 24 hours. For instance, if the spin axis of a rotating gyroscope is pointed at the sun, the end of the axis will seem to follow the sun as it crosses the sky. This is because the gyroscope holds its original position in an inertial frame of reference while the earth turns under it, causing the apparent motion. One exception is when the spin axis points toward the polar star. Then, there is no movement of the spin axis with respect to the observer’s surroundings, as the axis is parallel to the earth’s axis and points towards the poles.

The second interesting property of the gyroscope is its precession capability. Precession is the tendency of the gyroscope to move at right angles to the direction of any perpendicular force applied to it. If a force is applied to the gyroscope which has a component perpendicular to its rotational axis, the gyroscope does not move in the direction of the force. It starts to rotate, or *precess,* in a direction at right angles to the applied force. When the applied force is removed, the gyroscope stops its precessing motion. Precession makes the bicycle turn a corner when the rider leans to one side. This property can be illustrated using a bicycle wheel, mounted on an axle on which it is free to rotate. At first, the axle is supported at both ends while the wheel is made to rotate rapidly. If one support is removed, the wheel and the axle will tend to fall down. In addition, a reaction will be created which opposes the falling motion of the wheel, and instead causes the axle to appear to move horizontally about the remaining support. The removal of one support actually applies a torque to the axle. If a torque is applied to a rotating body that is not along the body’s axis of rotation, then the rotational axis moves in a direction at right angles to the direction of the applied force. Hence, when a downward force is applied at one end of the rotational axis of a spinning gyroscope lying horizontally, the resulting torque will cause the gyroscope to precess. During precession, the rotational axis will be moving horizontally about the point of support. The rate of precession, Ω, is proportional to the applied torque τ and perpendicular in direction (13):

$$\boldsymbol{\tau} = \boldsymbol{\Omega} \times I\boldsymbol{w} \tag{1}$$

where I is the rotational inertia of the rotor and $\boldsymbol{w}$ is the rotor spin rate. Gyroscopic precession is the key factor in the operation of the north-seeking gyrocompass discussed below.

When the spinning top is acted upon by a gravity-induced torque, the original rotational motion tries to align itself with the added rotational motion of the torque. In other words, the spin vector tries to align itself with the torque vector by chasing the torque vector.

Flywheel Gyroscopes. The main part of the flywheel gyroscope is the wheel, or *rotor,* illustrated in Fig. 1. Typical rotors employed in aircraft instruments may be smaller than 5 cm and make 35,000 rpm, and are usually made of metal or fluid. In the latter case, the fluid is enclosed within a hollow sphere inside the gyroscope and is rotated at high speed to produce the gyroscopic action.

An *axle* passes at right angles through the center of the rotor. Usually, the rotor is heavily weighted around the rim to increase its rotational inertia. One of the most important aspects of constructing a gyroscope is to mount the rotating wheel so that it is free of all unwanted torques. If this can be achieved, the spin vector of the gyroscope does not change from its initial value and always points in the same direction with respect to an inertial frame. This way, the gyroscope can function as a good reference direction system.

If the instrument is to be used in the gravitational fields of other bodies, the torques caused by the weight of the gyroscope must be eliminated. A gyroscope used on the earth, for example, is subject to the forces and torques due to gravity. To eliminate the torques, it is necessary to hold the gyroscope with a force applied at its center of mass, which is usually somewhere near the geometrical center of its rotor. It is very difficult to mount the gyroscope at this point. Thus, in order to be free of gravity, gyroscopes are placed in a *Cardan mount,* illustrated in Fig. 1. In the Cardan mount, the ends of the axle are mounted on ball bearings in a movable frame, or ring, called an *inner gimbal.* This inner frame is supported by bearings in an *outer gimbal.* The outer gimbal is mounted on bearings in a supporting frame, or *yoke,* by bearings along a diameter at right angles to the axis of the inner gimbal. Each of these three axes passes through the center of gravity of the entire system.

The number of gimbals determines the number of degrees of freedom of the gyroscope: If two gimbals are used, the gyroscope rotor is free to move in any direction without having to move the frame. If only one gimbal is used, the motion of the rotor is restricted, and it cannot assume certain positions without moving the frame. The center point of the rotor always remains at a fixed position within the gimbals no matter what the orientation of the axle is. The difference between two and three degrees of freedom can be observed in Fig. 3.

Three-Frame Gyroscopes. Unrestrained three-frame gyroscopes have little practical use, since their spin axes are subject to tilting and drifting due to the rotation of the earth. Three-frame gyroscopes are used in the *controlled state,* where the spin axis, by small continuous or intermittent applications of torque, is made to precess so that it oscillates around a mark fixed in relation to coordinates on the earth rather than in relation to space.

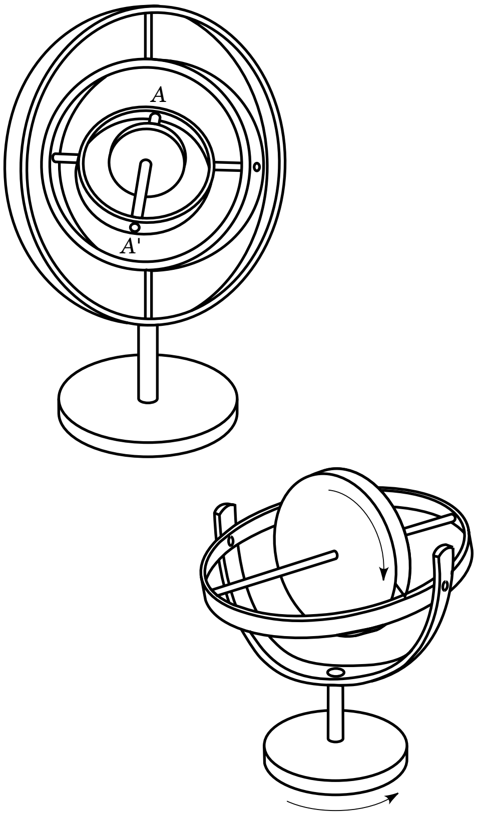

Figure 3. Three-frame gyroscope (top) and two-frame gyroscope (bottom). The number of frames determines the number of degrees of freedom of the gyroscope.

While the rotor of a three-frame gyroscope is spinning, if a slight vertical downward or upward pressure is applied to the horizontal gimbal ring at the two ends of the axle, the rotor axle will move at right angles in a horizontal plane. No movement will take place in the vertical plane. Similarly, if a sideways pressure is applied at the same point, the rotor axis will tilt upward or downward. A precession or angular velocity in the horizontal plane is caused by the application of a *couple* in the vertical plane perpendicular to that of the rotor wheel. A couple is a pair of equal and opposite parallel forces.

Controlled gyroscopes fall into three categories: north-seeking (meridian), directional, and gyrovertical (horizon indicator). The north-seeking gyroscope is used for marine gyrocompasses. In the settling (or normal) position, the spin axis is kept horizontal in the plane of a meridian as described later in the section on gyrocompasses. The directional gyroscope is used in aircraft and is sometimes called a self-leveling free gyroscope corrected for drift. Its spin axis is horizontal with directional properties, but the gyroscope does not seek the meridian plane automatically. The gyrovertical has its spin axis vertical and is used to detect and measure angles of roll and pitch. All these three-frame gyroscopes are *displacement gyroscopes* in that they can measure angular displacements between the framework in which they are mounted and a fixed reference direction, which is the rotor axis.

Two-Frame Gyroscopes. Suppose that with the rotor spinning with the spin axis in a horizontal plane, the base of the gyroscope is rotated uniformly in the horizontal plane (Fig. 3, bottom). A resistance due to the gyroscopic inertia will be felt. At the same time, the spin axis will begin to precess in the vertical plane and will continue to do so until the axis is vertical and all gyroscopic inertia disappears. If the same experiment is repeated, except that while the base is being turned in the horizontal plane, the precessional movement of the spin axis is stopped by the application of a force on the end of the shaft where it joins the gimbal ring, then the resistance to the turning motion of the hand due to gyroscopic inertia will cease to exist. The faster the base is turned, the greater the vertical downward force that must be exerted on the shaft to stop the precession. This force can be exerted by a spring arrangement [Fig. 4 (top)] or a U-shaped tube containing mercury fastened to the axis supports. This gyroscope measures the rate of change of azimuth and is used in aircraft and ships as a rate-of-turn indicator. Angular rate of roll in ships can be measured by applying the same principle. In this case, the spin axis is positioned at right angles to the fore-and-aft line and the rate of roll is measured about this line. This is illustrated in Fig. 4 (bottom).

These are velocity or *rate gyroscopes,* which must be distinguished from *displacement gyroscopes* described above. The sensitive or input axis of a rate gyroscope is at right angles to its spin axis, while with a displacement gyroscope the spin axis is directly along the input axis. For example, a north rate gyroscope and a north displacement gyroscope have their spin axes perpendicular to each other.

If the bearing mounts of the gyroscope were frictionless, no external torque would be transmitted to the rotating wheel, irrespective of the orientation in space. In practice, the bearings on which the gyroscope rotates are made with care to minimize friction. They must be assembled in windowless, air-conditioned rooms so as to eliminate dust inside the bearings, which can cause a gyroscope to fail. As an alternative to ball bearings, rotors can also be supported (floated) by a fluid or electrostatic or magnetic fields in so-called *flotation gyroscopes.* In the first case, the airtight inner gimbal is suspended in an inert fluid. Gimbal bearing friction is reduced because the buoyancy of the inner gimbal is neutral in the fluid. Flotation also increases resistance to shock and vibration. There is a diaphragm that seals the product and allows for fluid expansion as the outside temperature and/or pressure changes. Alternatively, the rotor is suspended with the aid of electrostatic fields in a vacuum to prevent any mechanical contact between the spinning ball and the outside case. In some cases, a beam of light reflected from reference marks on the surface of the rotor measures changes in orientation. Moving charges, however, produce magnetic fields and currents that interact with each other and with the earth's magnetic field, thus producing torques just as frictional forces do. Many missiles are guided by electrically suspended gyroscopes.

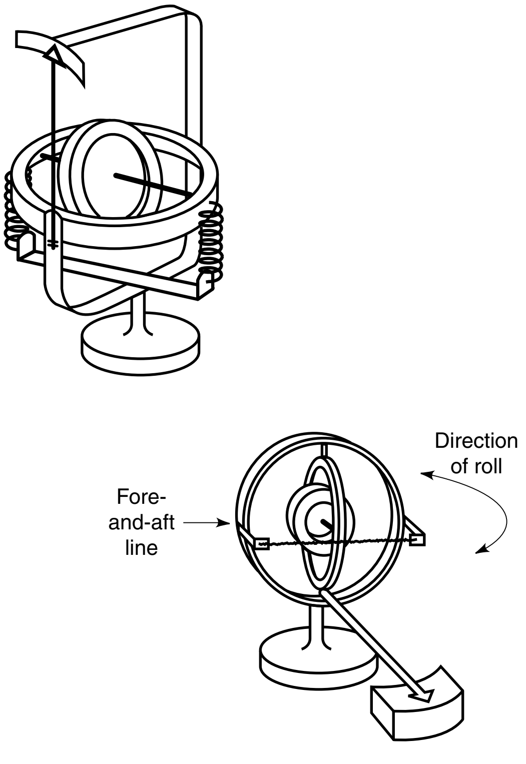

Figure 4. Rate gyroscopes for measuring rate of turn (top) and rate of roll (bottom). In the top figure, a spring arrangement is used to exert a force on the shaft to stop the precession. The amount of force exerted is a measure of rate of turn. In the bottom figure, the spin axis is positioned at right angles to the fore-and-aft line and the rate of role is measured about this line.

Since very little friction is produced in the bearings, only a small amount of power is required to keep the rotor turning. In most instrumental gyroscopes, the rotor is driven by a small self-contained electric motor or a small stream or jet of air that blows on the rotor.

The friction between the spinning wheel and the surrounding atmosphere also produces unwanted torques on the system. Such gaseous friction can be reduced by placing the gyroscope in hydrogen or in a vacuum. Over long periods of time, these combined torques, no matter how small, change the angular momentum of the gyroscope, causing it to drift.

After frictional torques have been minimized, a gyroscope can be used to measure applied torques resulting from forced angular motion. The applied torque, acting over a time interval, affects the original angular momentum by changing either the direction of the spin axis or the magnitude of the spin. Measurement of the change in angular momentum thereby provides information about the applied torque.

Modern Spinning Gyroscopes. A number of precision-machined gyroscopes are available on the market, costing between $10,000 and $100,000, depending on the accuracy. There have been recent developments and updates in mechanical gyroscope technology with the advent of solid-state electronics. A miniature gyro named GyroEngine (Gyration, Inc.) uses a conventional spin gyroscope in which motion is sensed around two independent axes using an optical sensor technique (14). The use of this technology greatly reduces the gyro's size and weight. An injection-molded, clear polycarbonate plastic is used for the housing and structural parts. Polycarbonate was selected because of its lower cost, high strength, ability to withstand a wide range of temperatures, and very good optical properties. Optical properties are important, since the optics needed for the sensor system are molded into the structure to reduce cost.

GyroEngine is a flotation-type, free-spinning, low-cost, low-power, two-degree-of-freedom gyroscope, about the size of a 35 mm film roll weighing only 40 g, that provides data in serial packets. The device is available as either a vertical gyroscope for measuring pitch and roll or a directional gyroscope for measuring yaw.

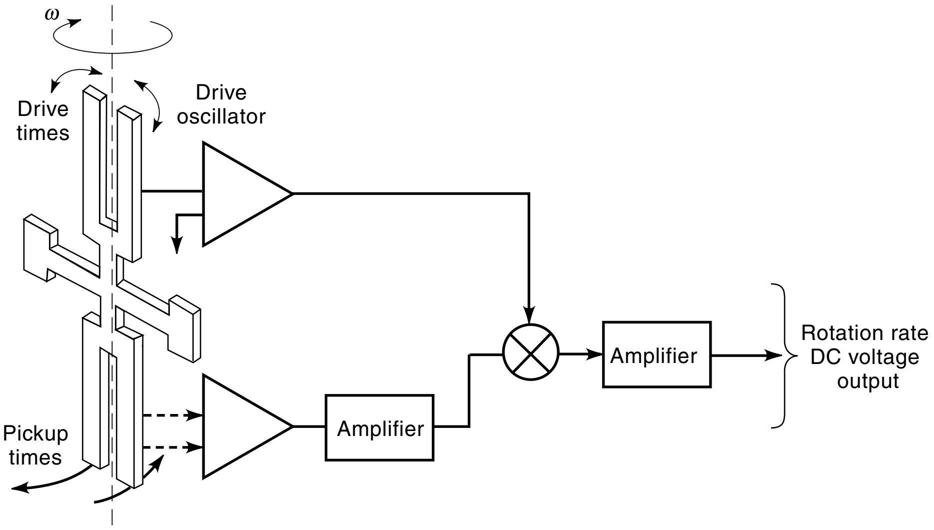

Figure 5. The block diagram of a quartz rate sensor. An oscillating tuning fork senses angular velocity by using the Coriolis effect. The linear motion of the tines is translated into an oscillating torque. After demodulation, a dc voltage is produced, which is proportional to the rate of rotation. (Courtesy of Systron Donner Inertial Division, Concord, CA.)

In a conventional gyroscope, rate data signals are passed in and out of the device through a series of precision slip rings. In the GyroEngine, a light-emitting diode is mounted inside the gimbal assembly and shines through a ring on the inner gimbal, which has a precision grating pattern mounted on it. A set of clear decals with printed optical diffraction gratings (moiré patterns) are mounted at four different places throughout the gimbal system. As the inner gimbal rotates, the light beam passing through the pattern on the ring is modulated in such a way that the motion of the gimbal is detected and tracked. The modulated light beam passes through the center of the gimbal bearing, where it is detected by a photoelectric diode sensor that is outside the gimbal system. The outer gimbal employs a similar optical sensing mechanism. The device reports gimbal position data digitally, eliminating the need for analog-to-digital conversion (ADC) and simplifying the electronics. The open collector outputs can readily be interfaced with digital circuits. The resulting digital signals are transmitted to a microcontroller for processing and output. The control electronics is included in the plastic housing rather than being external. The motor electronics is within the inner gimbal. Since much less signal processing is necessary, the output can be reported without delay (15).

The resolution of the device is 0.1 deg/rev. A typical drift rate is about 0.15 deg/s. The device costs a few hundred US dollars. Some of its advantages include reduction of the number of slip rings from six or more to two, output being digital rather than analog, data providing absolute position and direction of gimbals, and ability to report motion in real time.

Vibrating Gyroscopes

Quartz Gyroscopes. The concept of using a vibrating element to measure rotational velocity by employing the Coriolis principle has been used for more than 50 years. In fact, the idea developed long ago from the observation that a certain species of fly uses a pair of vibrating antennas to stabilize its flight.

Recently, vibrating quartz tuning fork technology has emerged for the production of microminiature, solid-state gyroscopes on a chip (16). These are similar to the mechanisms used in digital wristwatches to provide the frequency or time reference.

A basic quartz rate sensor (QRS) has essentially two components: drive and pickup as shown in the block diagram in Fig. 5. The drive portion functions exactly like a simple tuning fork: Exploiting the piezoelectric properties of quartz, an electrical signal applied to the tuning fork causes it to vibrate at a fixed amplitude. Drive tines are the active portion of the sensor, and are driven by an oscillator circuit. Each fork tine has a mass and an instantaneous radial velocity that changes sinusoidally as the tine moves back and forth. As long as the fork's base is stationary, only the drive fork vibrates as it responds to signals from an oscillator. The momenta of the two fork tines exactly cancel each other and there is no net energy transfer from the tines to the base. The amount of power required to keep the fork ringing is only about 6 μW (17).

Another similar fork is employed as a pickup element to produce the output signal. The passive pickup tines of this fork are the sensing portion of the sensor that vibrate only when the device rotates. When the tuning fork is rotated around its axis of symmetry, the Coriolis effect causes the pickup fork to vibrate. According to the Coriolis principle, a linear motion within a rotating framework will have some component of velocity that is perpendicular to that linear motion. Thus, each tine will generate a force perpendicular to the instantaneous radial velocity of each of the other tines according to the following equation:

$$\boldsymbol{F}_c = 2m\boldsymbol{w} \times \boldsymbol{v}_r \tag{2}$$

where m is the tine mass, $\boldsymbol{w}$ is the rotation rate, and $\boldsymbol{v}_r$ is the radial velocity of the tines. Since the radial velocity of the tines is sinusoidal, the resultant force on each tine is also sinusoidal, equal and opposite in direction and in phase with $\boldsymbol{v}_r$. Hence, the oscillating torque created at the base of the drive tine fork is directly proportional to the input angular rate. The sinusoidal torque variation causes the pickup tines to begin moving tangentially to the rotation and at the same frequency as the drive vibration. The output reverses sign with the reversal of the input rate since the oscillating torque produced by the Coriolis effect reverses phase when the direction of rotation reverses. If there is no rotation, the pickup tines will not move, indicating a zero-rotation input.

The resulting vibration (pickup signal) from this second fork can be electronically analyzed to measure the angle and

Figure 6. The GyroChip II solid-state gyro which employs a quartz tuning fork. Several thousand of these items can be mass-produced in a single batch. (Photo courtesy of Systron Donner Inertial Division, Concord, CA.)

intensity of movement. The signal is first amplified and then demodulated using the drive frequency as a reference. After further amplification and signal shaping, a dc signal output is produced that is directly proportional to the input angular rate. Signal-processing electronics are fairly simple and usually custom developed on chip, and included within the same package as the sensing element.

QRSs are fabricated chemically from a wafer of single-crystal, synthetically grown piezoelectric quartz material using photolithographic and chemical etching processes characteristic of the microelectronics industry and micromachining techniques (18). Hence, several thousand of these items can be mass-produced in a single batch. Dual tuning forks on a QRS are pure crystal and nearly transparent. An example quartz gyro, Gyrochip II by Systron and Donner Inertial Division, is illustrated in Fig. 6. In another device by the same manufacturer, called MotionPak (see Fig. 7), three QRSs are used in conjunction with three linear accelerometers in order to realize a six degree of freedom inertial sensor cluster.

Figure 7. The MotionPak inertial sensor, comprising three quartz rate sensors and three linear accelerometers with a total of six degrees of freedom. (Photo courtesy of Systron Donner Inertial Division, Concord, CA.)

The main advantage of quartz gyros is expected to be lower cost of manufacturing and maintenance, which is one-third to one-half the cost of fiber-optical equivalents. Other advantages include superior reliability, design simplicity, low power consumption, small size, low weight, ruggedness, and long operating life. A conventional flywheel rate gyroscope may have 100 to 300 separate precision parts, and a fiber-optic gyro (FOG) may have 10 to 20 parts and many meters of fiber, but a quartz gyroscope has only a single part in its sensing portion. These can withstand high shocks and accelerations of up to 10,000 times the force of gravity resulting from gun or projectile launching. A typical quartz gyroscope has a 2 cm diameter, whereas a comparable fiber-optic gyro would measure 4 to 8 cm.

The typical accuracy of quartz gyroscopes is around 1 to 2 deg/min, which is comparable to that of conventional medium-accuracy rate or rate-integrating gyros. The target markets for FOGs and QRSs differ according to performance capability. FOGs have much higher accuracy than QRSs, in the range of 1 to 10 deg/h. As microelectronic gyros develop further, they will be challenging FOGs for lower-accuracy applications, especially in single-axis configurations. However, three-axis FOGs will remain cost-competitive because in multiplexed FOG configurations, one set of electronics is shared by all three axes. On the other hand, in three-axis quartz gyros, three sets of electronics are used, so a three-axis quartz gyroscope costs as much as three times what a single axis gyro costs.

QRSs have several disadvantages compared to FOGs. Key performance parameters such as bias drift and scale factor are unstable over the long term (19). The scale factor is a measure of how accurate and stable a signal is over time. Secondly, the turn-on to turn-on bias may be large. A large turn-on to turn-on bias means that gyroscope drift has different values on one day and the next. The vibration and shock performance is usually uncertain. Part of the ongoing research is focused on improving the accuracy of quartz gyroscopes.

Hemispherical Resonator Gyroscope. The solid-state hemispherical resonator gyro (HRG) is based on the rotation-sensing properties of a ringing wine glass, first noticed by the British physicist G. H. Bryan in 1890. The modern implementation of this principle involves a gyro comprising three fused-quartz parts, a wine-glass-shaped resonator, an external forcer housing, and a pickoff housing on the unit's base. These are joined by indium solder and employ metalized thin-film electrodes and conductors. When voltage is applied to the resonator, it flexes up to 0.00025 cm and creates a low-amplitude wave that can be sensed by the pickoffs. The precession of this wave is correlated with the rotation angle. There are no bearings or surfaces in the HRG subject to wear, and the interior of the device is maintained in a high vacuum. A typical service time is expected to be 20 years with mean time between failures (MTBF) of more than 150,000 h. Precision manufacturing is critical in the operation of this gyroscope.

Murata Gyrostar. Another type of vibrating gyroscope is the Gyrostar, which is a small relatively inexpensive single-axis piezoelectric rate gyroscope originally developed for the automobile market and active suspension systems by Murata Manufacturing Company in 1991 (20). A picture of the device is provided in Fig. 8.

The principle of operation is again based on the fact that a proportionate Coriolis force results if angular velocity is ap-

Figure 8. The Gyrostar manufactured by Murata Electronics. This is a small, relatively inexpensive, single-axis piezoelectric rate gyroscope originally developed for the automobile market and active suspension systems. (See B. Barshan and H. F. Durrant-Whyte, *IEEE Trans. Robot. Automa.* **11** (3), 328–342, June 1995. Copyright IEEE, 1995.)

plied to a vibrating object. The sensor element unit comprises a 40 mm long triangular prism made of a special substance called *elinvar* (elastic invariable metal), which is a nickel-chromium-steel alloy with a very small coefficient of thermal expansion to ensure good dimensional stability (21).

Both the excitation and the detection units employ piezoelectric ceramics. On each of the three vertical faces of the bar, a PZT-6 ceramic piezoelectric transducer is placed as illustrated in Fig. 9. The flexural resonance frequency of a triangular prism is given by (22):

$$f_{\mathrm{n}} = \frac{ka}{4\pi l^2}\sqrt{\frac{E}{6\rho}} \tag{3}$$

where k is a constant, a and l are the width and length of the bar respectively, E is Young's modulus of elasticity, and ρ is the density of the bar material.

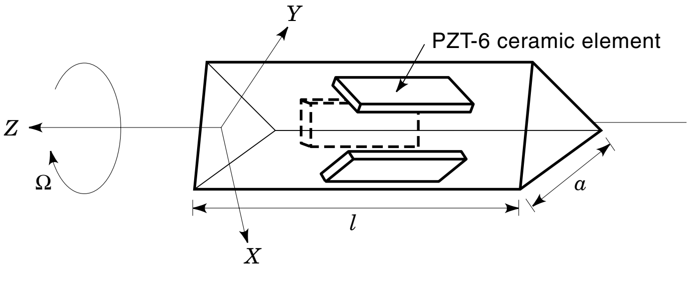

Figure 9. The triangular prism of Gyrostar with a piezoelectric ceramic transducer placed on each of the three faces of the bar. Excitation of the prism at its resonant frequency by two of the transducers causes vibrations to be picked up by the third transducer.

Excitation of the prism by the left and right transducers at the resonant frequency $f_{\mathrm{n}} = 7.85$ kHz of the bar, perpendicular to its face, causes vibrations to be picked up by the third transducer, which provides feedback to the drive oscillator (22). The equilateral triangular prism allows the driving transducers to be configured in the direction of the compound vibration mode. The same elements can be used for both excitation of the bar and detection of the resulting Coriolis forces (23,24).

The gyroscope detects the angular rotation by measuring the differential output of the left and right transducers. If the sensor remains still, or moves in a straight line, the signals produced by the pickup transducers are exactly equal. If the prism is rotated around its principal axis, a Coriolis force proportional to the rate of rotation w about the z axis is created according to the equation

$$F_{\mathrm{c}} = 2mw \times v_y \tag{4}$$

where F_{c} is the Coriolis force, m is the equivalent mass of the prism, and v_y is the rate of change of position of the element in the y direction. The actual rotation rate w can be determined by measuring the amplitude of the vibration at the pickup transducer. As the bar distorts due to the Coriolis forces, one detector output increases while the other decreases. The differential output is amplified to yield an analog voltage proportional to the angular velocity of the vehicle around the principal axis of the device. A block diagram of the device is provided in Fig. 10. The maximum rate that can be measured with Gyrostar is ±90 deg/s within its linear range, with a response time of 0.02 s.

The unique geometry of the Gyrostar provides better performance than tuning-fork gyros at a significantly lower price (23). On the other hand, there is still thermally induced drift due to thermal gradients within the element and the mismatches in the material thermal expansion rates at the elinvar–ceramic interfaces. An evaluation of this gyroscope and modeling of its drift error is provided in Ref. 25.

The main application of the Gyrostar has been directional control in car navigation systems by keeping track of turns for short durations when the vehicle is out of contact with reference points derived from the additional sensors. Other target applications include video camera stabilizers, position and posture control of moving objects, robotics, and controlling the direction of satellite antennas on moving objects. The cost of the device is several thousand Japanese yen.

Optical Gyroscopes

Active Ring-Laser Gyroscopes. The operating principle of the active ring-laser gyro (ARLG), which is an angular-rate sensor, is based on the Sagnac (interferometer) effect. The basic device consists of two laser beams traveling in opposite directions around a closed-loop path. In 1966, Schulz-DuBois idealized the RLG as a hollow doughnut-shaped mirror in which the closed-loop path has circular shape (26).

Conventional RLGs include a source of lasing and optical mirrors. A circulant cavity or waveguide is made out of a low-expansion, quartzlike glass–ceramic material, and is filled with a gas such as helium–neon, which acts as the lasing medium. When the gas is excited, photons are emitted and begin to circle around in the cavity in both directions. In effect, this creates two counterrotating beams of coherent laser

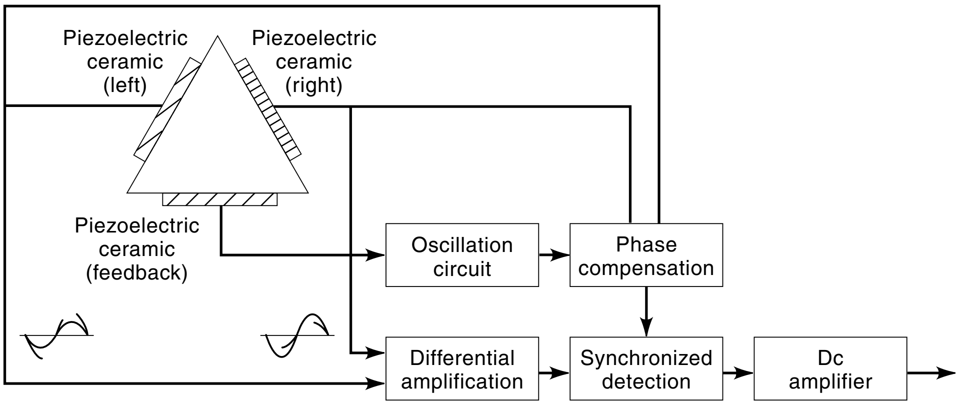

Figure 10. Block diagram of the Gyrostar. The differential output is amplified and phase compensated to yield an analog dc voltage proportional to the rate of rotation around the principal axis of the device.

light, which create a stationary standing wave with intensity nulls and peaks as shown in Fig. 11, regardless of whether the gyroscope is rotating or not. The interference pattern tends to stay fixed in inertial space, and the path of the light varies with the rotational motion of the gyroscope. If the gyroscope cavity rotates in the counterclockwise (CCW) direction, then the CCW-propagating beam will traverse a slightly longer path than under stationary conditions. The path of the clockwise (CW) traveling beam will be shortened by the same amount. Consequently, a phase shift results between the two laser beams, which can be monitored. The magnitude of the change in the path length ΔL is given by

$$\Delta L = \frac{4\pi r^2 w}{c} \tag{5}$$

where r is the radius of the circular beam path, w is the angular velocity of rotation, and c is the speed of light in the medium. Since the change in path length is directly proportional to w, rotational rate measurement relies on accurate measurement of the change in the path length. The invention of the laser provided the means of accomplishing this measurement. A major portion of the light impinging upon the surfaces of the mirrors is reflected by the mirrors, and a minor portion is transmitted through at least one of the mirrors. The light transmitted through is measured by a system that includes optical sensors and a data processor to permit the device to detect changes in rotational motion.

In order for lasing to occur, the round-trip beam path must be precisely equal in length to an integral number of wavelengths at the resonant frequency. Thus, the wavelengths of the two counterrotating beams must change when rotation occurs. The resulting frequency difference or beat frequency Δf, between the two beams is given by (26)

$$\Delta f = \frac{2frw}{c} = \frac{2rw}{\lambda} \tag{6}$$

where f is the frequency and $\lambda = c/f$ is the wavelength of the beam.

A doughnut-shaped resonator cavity would be practically difficult to realize. For an arbitrary cavity, the equation becomes

$$\Delta f = \frac{4Aw}{P\lambda} \tag{7}$$

where A is the area enclosed by the closed-loop beam path and P is the perimeter of the beam path. For single-axis gyros, the closed-loop path is most often formed by aligning three highly reflective mirrors to create a triangular path as shown in Fig. 12. Systems similar to Macek's early prototype employ four mirrors to create a square path. The mirrors are usually mounted on a monolithic glass–ceramic block with machined ports for the cavity bores and holes (27).

A modern triaxial design employs six mirrors, centrally mounted on the faces of a cube. Within the enclosed volume of the glass–ceramic block, three mutually orthogonal and independent RLGs are placed such that each employs four of the mirrors. Hence, each mirror is shared by two of the axes (28). A picture of an example triaxial gyroscope is given in Fig. 13. To avoid magnetic sensitivities, the most stable sys-

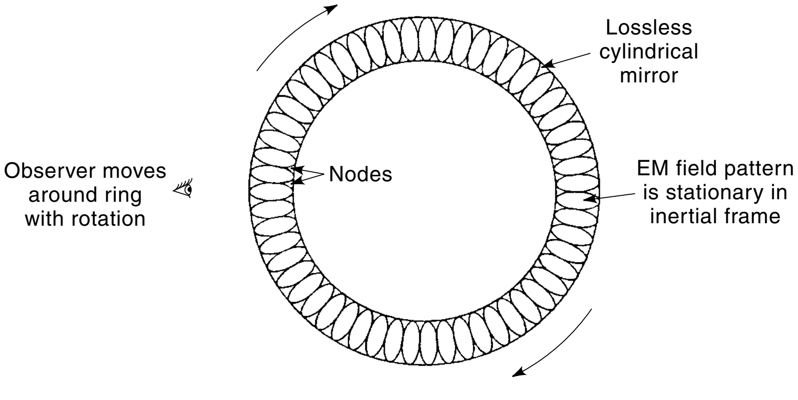

Figure 11. Standing wave pattern created by two counterrotating laser beams in an idealized RLG. The interference pattern tends to stay fixed in inertial space, and the path length of the light varies with the rotational motion of the gyroscope.

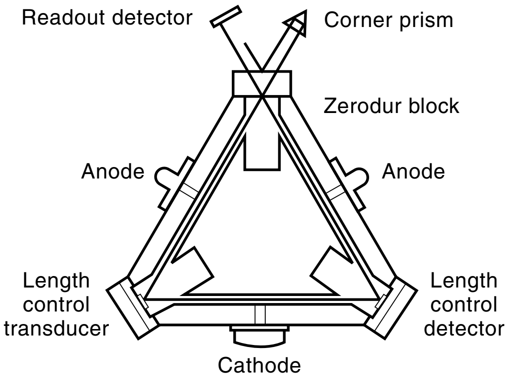

Figure 12. A triangular configuration for a single-axis RLG employing dual anodes. Three highly reflective mirrors have been used to create the triangular path. (Courtesy of John Wiley & Sons, Inc., New York; adapted from Ref. 2.)

tems employ linearly polarized light and minimize circular polarization (8).

Reliability and robustness are among the advantages of ARLGs. The main disadvantage of the ARLG is a phenomenon called *frequency lock-in,* which occurs at low angular rates when the two beams "lock" together in frequency (29). As in any physical system that sustains two modes of oscillation, problems occur when the two frequencies approach each other. Energy is exchanged between the two modes and the frequencies tend to lock and become one, violating Eq. (7). This trading of energy or coupling is mainly caused by periodic modulation of the gain medium or other effects due to a very small amount of backscattered radiation from the imperfect mirror surfaces (2). The result is a small deadband region for low rotational rates, within which no output signal is observed. Above the lock-in threshold, the output converges to the ideal linear response curve in a parabolic fashion.

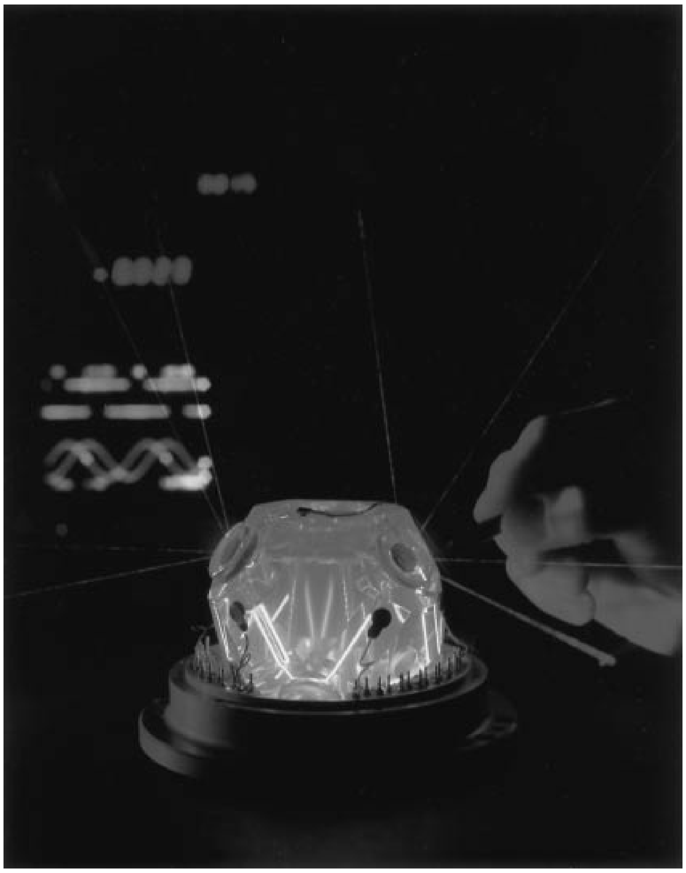

Figure 13. An example triaxial monolithic RLG operating at 632.8 nm. (Photo courtesy of Kearfott Guidance & Navigation Corporation, Inc., Wayne, NJ.)

One way to solve the frequency lock-in problem is by improving the quality of the mirrors in order to reduce backscattering. A more practical technique for reducing lock-in is to use a biasing scheme to shift the operating point away from the deadband zone. This is commonly accomplished by *mechanical dithering,* where the gyroscope assembly is oscillated back and forth about the principal axis (typically ±100 arc-seconds at 400 Hz) by using a stiff dither flexure suspension acting like a rotary spring. Piezoelectric transducers provide the force to rotate the laser cavity block. Disadvantages of this method include increased system complexity, increased failure rate due to moving parts, and crosstalk between axes. In addition, it introduces a random-walk error increasing as the square root of the time. After the application of randomized dither, residual lock-in falls just under 0.002 deg/h and random-walk error remains between 0.001 and 0.003 deg/h$^{1/2}$. Hence, dithering is not suitable for high-performance systems such as those used for flight control.

Other methods of reducing the frequency lock-in include the use of extremely short-duration laser pulses (30–33), the use of techniques based on nonlinear optics (8), or removing the lasing medium and using a passive resonator as described below.

The RLG is limited by the quantum noise level due to spontaneous emission in the gain medium (34). Other sources of error include stability of the mirror's optical axis, mirror surface erosion, outgassing of epoxy material within the laser cavity, precision of path length, current, and dither control, all of which affect the gyro bias error. Yet, the ARLG provides the highest sensitivity and is perhaps the most accurate implementation to date. The main problem with the ARLG is its high cost. If the cost can be lowered, the device will be more widely used.

Aronowitz (35), Menegozzi and Lamb (36), Chow et al. (27), Wilkinson (37), and Udd (2) discuss the theory of RLG and its fiber-optic derivatives in detail. Ezekiel and Arditty provide a tutorial review of the technologies, and an extensive bibliography on earlier work (34).

Passive Ring-Laser Gyroscopes. In the passive ring-laser gyroscope (PRLG), the laser source is external to the ring cavity as in Fig. 14, providing a solution to the frequency lock-in problem. This configuration also eliminates the problems caused by changes in the optical path length within the interferometer due to variation in the index of refraction of the gain medium (27). One problem, however, is that the theoretical limit for the photon shot noise level is higher than that of the ARLG (34).

The main disadvantage of both active and passive RLGs is the bulky packaging compared to those gyroscopes based on fiber-optic technology. In addition, production of RLGs requires high-tolerance machining and clean-room assembly. As

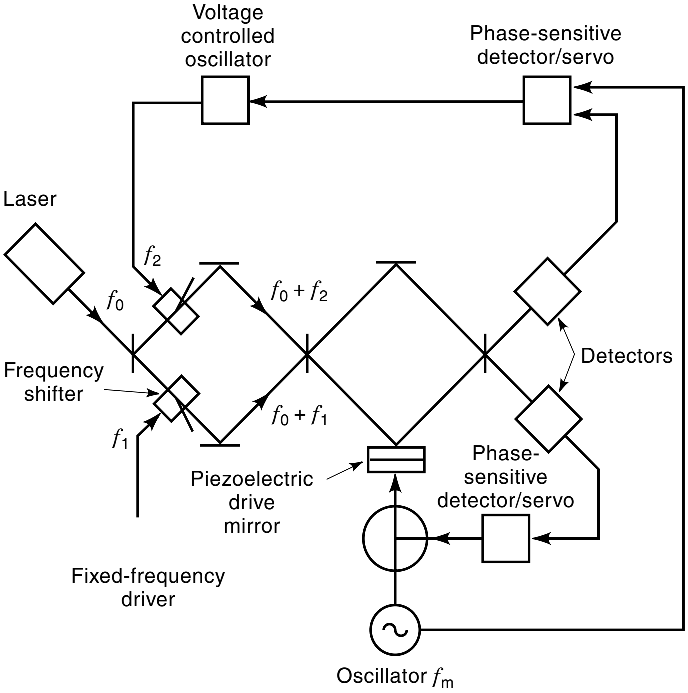

Figure 14. Block diagram of passive cavity ring-laser gyro. The laser source is external to the ring cavity, providing a solution to the frequency lock-in problem. (Courtesy of John Wiley & Sons, Inc., New York; adapted from Ref. 2.)

a result, the *resonant fiber-optic gyroscope* (RFOG) has emerged as the most popular of the resonator configurations (38).

Like RLGs, FOGs are angular-rate sensors based on the Sagnac effect. Basically, a long fiber-optic pathway is created and wound into coils. A single beam of light is split, with the two parts being sent in opposite directions through the optical fiber. A low-coherence source, such as a superluminiscent diode, is typically employed to reduce the effects of noise (39). The primary source of noise is backscattering within the fiber and at any interfaces. Consequently, in addition to the primary mode, there are also a number of parasitic secondary modes that yield secondary interferometers (40). The limited temporal coherence of the broadband light source causes any interference due to backscattering to average out to zero, making the system sensitive only to the interference due to the primary mode (34,40). A simplified block diagram is provided in Fig. 15.

The glass fiber forms an internally reflective waveguide for the beams of light. In essence, it replaces the bulky doughnut-shaped cavity first suggested by Schulz-DuBois. A *step-index multimode fiber* comprises a core region with a high index of refraction surrounded by a protective cladding with a lower index of refraction to keep the light in the core region through total internal reflection (41). If the core diameter is much larger than the wavelength of the light, a number of rays following different-length paths can simultaneously propagate down the fiber. Such multimode operation is clearly not desirable in gyro applications. If the diameter of the core is sufficiently reduced to approach the operating wavelength, only a single mode can propagate (41). *Single-mode fiber* is employed to ensure that the two counterrotating beams follow identical paths when the gyro is stationary. The fiber is also chosen to be of the *polarization-maintaining* type, since light of different polarization states travels through an optical fiber at different speeds (9,41).

Mainly, two types of FOG exist: interferometric (IFOG) and resonator (RFOG). When the two counterrotating laser beams meet at the end of the pathway, the two beams are compared. If rotation has taken place, the two beams will differ in some way, and the difference can be detected. If this is done interferometrically, the device is called an IFOG. More than 95% of existing FOG applications employ the IFOG, although the RFOG has been becoming more widespread recently. IFOGs can be further classified as open-loop and closed-loop gyroscopes as described below.

Open-Loop Interferometric Fiber-Optic Gyroscopes. The number of fringes of phase shift introduced by gyro rotation is given by (2)

$$Z_R = \frac{LD}{\lambda c} w \qquad (8)$$

where L is the length of optical fiber in the loop, D the diameter of the loop, λ the wavelength of light, c the speed of light in vacuum, and w the rotational rate. The stability of the scale factor relating the phase shift to rotational rate is dependent on the stability of L, D, and λ (34). Typically, an IFOG operates over $\pm\pi/2$ phase shift with a theoretical sensitivity of 1 μrad or less (42). Increasing L by the use of multi-

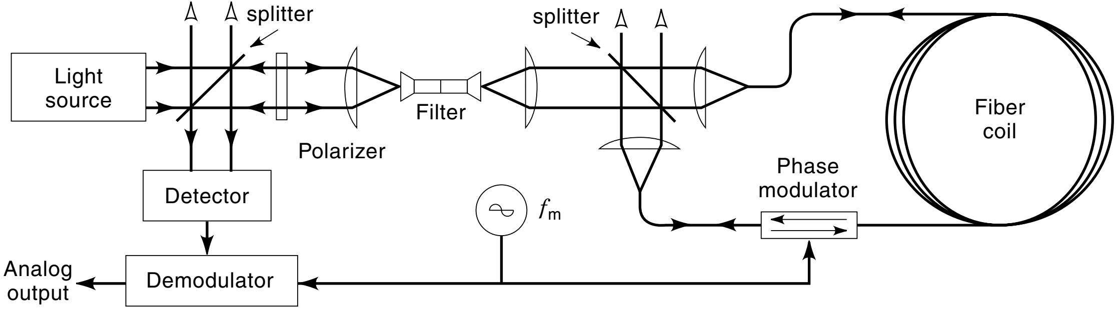

Figure 15. Simplified block diagram of an open-loop IFOG. A single beam of light is split, with the two parts propagating in opposite directions through the optical fiber coil. After demodulation, an analog output is produced which is proportional to the rate of rotation.

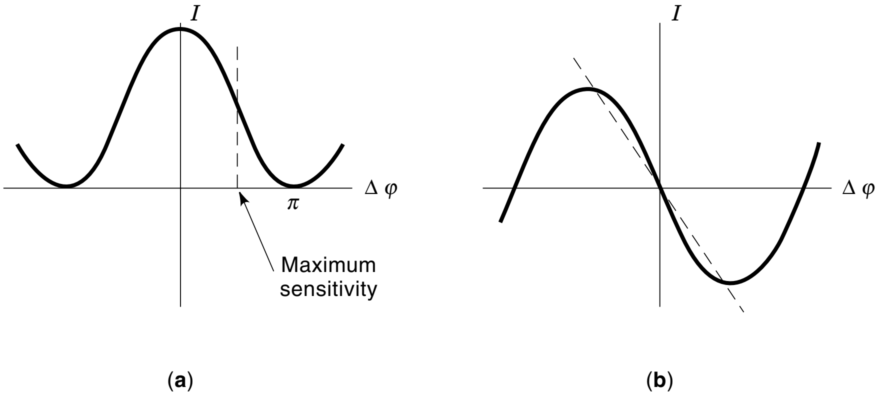

Figure 16. Detected intensity versus phase shift (a) and output of demodulator (b) for the analog open-loop IFOG. The symmetry of the original intensity pattern, shown in (a), does not allow distinguishing the direction of rotation. By introducing a phase shift of $\pi/2$ to the two beams, the operating point is shifted to the region of maximum sensitivity as shown in part (b).

ple turns of fiber enhances resolution by effectively multiplying the change in the path length due to the Sagnac effect by a factor N equal to the integer number of turns (2). The optimal length is of the order of several kilometers, after which the fiber attenuation (typically 1 dB/km) begins to degrade performance (34). This large amount of fiber required represents a significant percentage of the overall system cost.

For FOGs the main accuracy limit is not optics but noise in the electronic control loops. The accuracy of FOGs depends on fiber length and coil diameter used as implied by Eq. (8) above. FOGs typically operate at one of three wavelengths: 0.86, 1.33, or 1.55 μm (42). The shortest wavelength is optimum for a precision FOG, since it offers the greatest sensitivity. In contrast, longer wavelengths are preferable for telecommunication systems because of lower signal attenuation.

A minimum-configuration open-loop FOG consists of an optical source (such as a semiconductor diode light source), source–detector directional coupler, polarizer, coil directional coupler, and an optical-fiber coil (Sagnac ring). The source–detector coupler is not part of the Sagnac interferometer and serves mainly to provide isolation between the broadband optical source and the photodetector. When the two counterrotating laser beams meet at the end of the pathway, the fringe pattern created due to interference is inspected. Rotation of the path compresses the fringes in one direction and expands the fringes in the other direction, resulting in a changed pattern in the fiber. The intensity pattern caused by constructive and destructive interference, shown in Fig. 16, is in the form of a cosine, which is symmetric and cannot distinguish between CW and CCW rotation. The peak intensity occurs at zero rotation rate, where the sensitivity of the intensity to small changes in rotational rate is minimum. To overcome these problems, the two beams are phase-modulated to introduce nonreciprocal phase shifts (2). If a phase shift of $\pi/2$ is introduced, the operating point is shifted to the region of maximum sensitivity and the direction of ouput can be determined from the sign of the output (34). The return signal from the interferometer traverses the laser and is recovered by a photodetector behind the rear laser facet. This signal is distinguished from the laser signal by the bias modulation. This minimal configuration eliminates at least one directional coupler, the separate photodetector, and at least two fiber splices.

The disadvantages of this open-loop configuration are the nonlinearity of the input–output relationship, bias instability, the long length of optical fiber required relative to other FOG designs, limited dynamic range in comparison with ARLGs, and the sensitivity of the scale factor to analog component drifts/tolerances and light source intensity (43). On the other hand, it offers reduced manufacturing costs, high tolerance to shock and vibration, insensitivity to gravitational effects, quick startup, and fairly good sensitivity in terms of bias drift and random walk coefficient. The coil geometry is not critical. Therefore open-loop FOGs are more suitable for low-cost systems for low- to medium-accuracy applications such as gyrocompassing in automobile navigation, pitch and roll indicators, and attitude stabilization (44). Hitachi Cable, Ltd., Tokyo, has developed several IFOGs for a number of industrial and commercial uses such as automotive applications, mobile robotic systems, and agricultural helicopters (45,46).

A popular example of an open-loop IFOG is the Andrew AUTOGYRO®, which is a single-axis all-fiber rate sensor that includes an interface to the vehicle odometer and backup lights for use in dead-reckoning navigation (47) (Fig. 17). The device integrates angular rate data and odometry information over an interval, and combines these into a serial digital data output. The sensing element is a coil fabricated from elliptical-core, polarization-maintaining optical fiber which does not depend on stress-inducing members and operates from unconditioned vehicle power. The signal-processing electronics are stable with time and temperature, and the unit does not need to be recalibrated. An internal temperature sensor output enables further calibration in more accuracy-demanding applications. The packaging is rugged, consisting of an aluminum housing with weather-resistant gaskets.

Analog and digital output versions are available. The analog signal is the angular rate output, whereas the digital output is the result of integration of the rate output, which can be interpreted as either the incremental angle change during the measuring interval or the average rate. A wide analog bandwidth is maintained while reducing the output data rate. All required voltages are generated internally from a single, wide-range input voltage that can be directly connected to vehicle power.

The lack of moving parts implies longer life. Among other advantages of the device are stable operation, lack of sensitivity to rotation about or acceleration along other axes, good resolution, threshold and dynamic range, resistance to shock and vibration, high reliability, ease of interfacing, and freedom from preventive maintenance.

The device can detect input rotation rates between ±100 deg/s with a minimum detectable rotation rate of ±0.05 deg/s.

Figure 17. Picture of the AUTOGYRO® Navigator by Andrew Corporation. This is an example of an open-loop, all-fiber, single-axis IFOG. (Photo courtesy of Andrew Corporation, Orland Park, IL.)

The AUTOGYRO® is used in a continuous positioning system (CPS) costing about 3000 US dollars, comprising the AUTOGYRO® and a GPS receiver. The CPS is used in automated bus stop announcement systems and emergency vehicles such as ambulances, police cars, and fire trucks. The price of the AUTOGYRO® is under a thousand US dollars. A more detailed discussion of the AUTOGYRO® is provided in Refs. 48 and 49.

Closed-Loop Interferometric Fiber-Optic Gyroscopes. For applications demanding higher accuracy, the closed-loop FOG is more suitable, with drifts in the average 0.001 to 0.01 deg/h and scale-factor stabilities greater than 100 ppm (43). In closed-loop systems, an active torquing feedback loop into a frequency or phase-shifting element is employed to cancel the rotationally induced phase shift (2). Since the system is always operated around a zero phase shift, the gyro accuracy and drift are improved, and intensity variations in the light source and analog component tolerances have an insignificant effect (34). Closed-loop systems, however, rely on costly high-speed optical and electronic components.

A simplified block diagram of a closed-loop IFOG is illustrated in Fig. 18. The output of the demodulator is passed to a servo amplifier that drives a nonreciprocal phase transducer (NRPT), which is typically an electro-optic frequency shifter placed within the fiber interferometer (34). The NRPT introduces a frequency difference Δf between the two beams, resulting in a fringe shift Z_F given by (2)

$$Z_F = -\frac{\Delta f\, Ln}{c} \tag{9}$$

where n is the index of refraction and c is the speed of light. The linearity and stability of the gyro depend only on the NRPT (34).

To null out the phase shift at the detector, the fringe shift Z_R due to gyro rotation must be precisely canceled out by the fringe shift Z_F due to the relative frequency difference of the two beams:

$$Z_R + Z_F = 0 \tag{10}$$

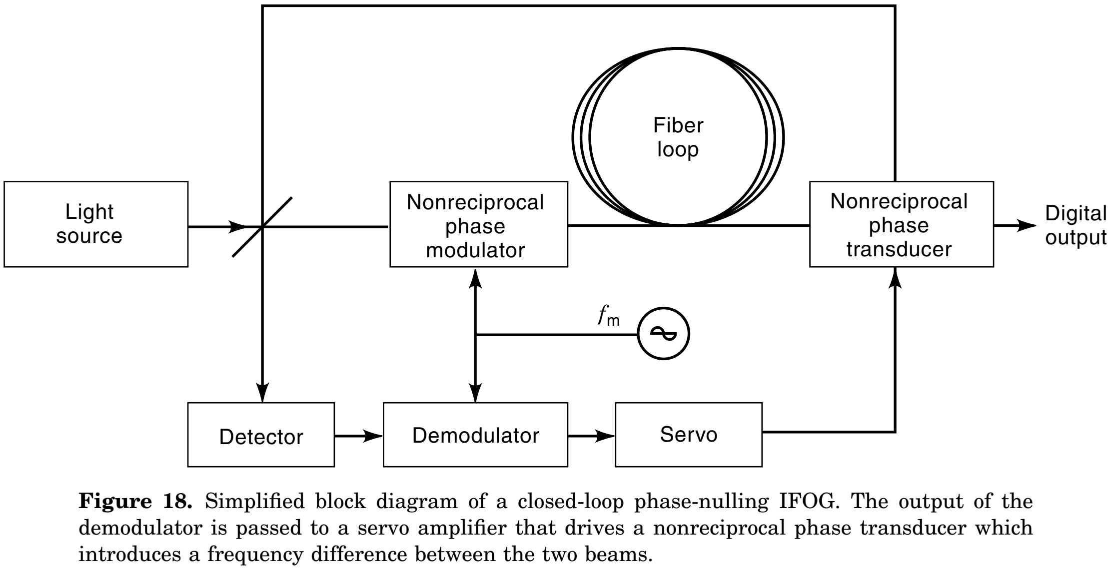

Figure 18. Simplified block diagram of a closed-loop phase-nulling IFOG. The output of the demodulator is passed to a servo amplifier that drives a nonreciprocal phase transducer which introduces a frequency difference between the two beams.

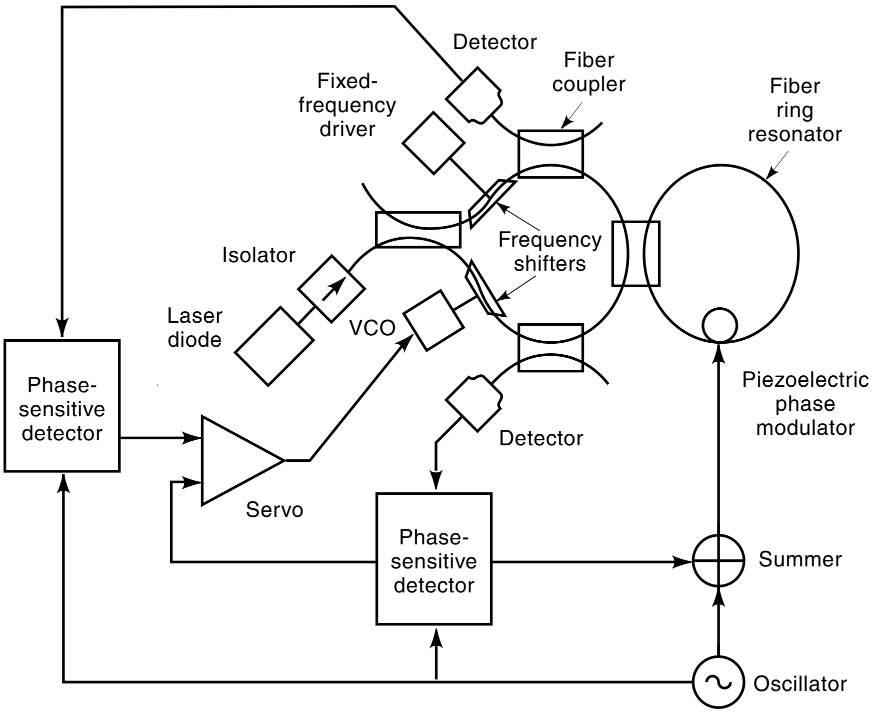

Figure 19. Block diagram of a fiber-optic ring resonator. Frequency-modulated light is coupled from a laser source into the resonant loop in both directions. The output coupler samples and detects the intensity of the energy in the loop. (Courtesy of John Wiley & Sons, Inc., New York; adapted from Ref. 2.)

Substituting Eqs. (8) and (9) for Z_R and Z_F and solving for Δf yields (2,34,44)

$$\Delta f = \frac{4AN}{n\lambda L}w = \frac{4A}{n\lambda P}w = \frac{D}{n\lambda}w \tag{11}$$

where A is the area of the fiber loop, N the number of turns in the loop, and P and D the loop perimeter and diameter respectively.

The gyro output Δf is thus inherently digital, as opposed to an analog dc voltage level, and also linear. However, closed-loop digital signal processing is considerably more complex than the analog signal processing employed in open-loop IFOGs.

Resonant Fiber-Optic Gyroscopes. The resonant fiber-optic gyro (RFOG) has evolved as a solid-state derivative of the PRLG described above. A block diagram is provided in Fig. 19. A passive resonant cavity is formed from a multiturn closed-loop of optical fiber. Frequency-modulated (FM) light is coupled from a laser source into the resonant loop in both the CW and CCW directions. For the case of no motion, maximum coupling occurs when the frequency of the laser during the FM sweep is such that the perimeter of the loop is an integral multiple of the wavelength (38). If the loop is rotated, the path lengths for the two beams will no longer be equal and the resonant frequencies shift accordingly. The output coupler samples and detects the intensity of the energy in the loop. The demodulated output at the detectors will show resonance peaks separated by a frequency difference of Δf given by (38)

$$\Delta f = \frac{D}{\lambda n}w \tag{12}$$

In practice, the frequency of the laser is adjusted to maintain resonance in one direction, and an electro-optical frequency shifter is employed to drive the other direction into resonance (44). This results in a frequency shift twice that induced by the Sagnac effect.

Advantages of RFOG are high reliability, long life, quick startup, and light weight. It requires 10 to 100 times less fiber in the sensing coil than the IFOG configuration. Since the optical fiber can be as short as 50 to 100 m, the size of these gyros is comparable to that of a spool of thread. RFOGs are limited by the same shot-noise level as IFOGs (38). According to Sanders, this is due to the fact that light traverses the loop multiple times, as opposed to once in the IFOG. Two disadvantages are the need for a highly coherent source and the need for extreemly low-loss fiber components (43).

Fiber-Optic Gyroscopes. Currently, RLGs are used for navigation applications requiring high accuracy, whereas FOGs are used for medium-accuracy applications such as in motion sensors. FOGs have certain advantages over RLGs. The latter rely on an active source of lasing for their operation and are very expensive to manufacture. FOGs do not require a coherent source, and their operation does not depend on a high-performance cavity, significantly reducing manufacturing costs (50). The mass production price of FOGs is estimated to be one-third that of comparable RLGs. Utilization of optical fiber in FOGs provides considerably greater ruggedness. Among other advantages of FOGs are light weight, low power consumption, small size, potential for mass production, little or no lock-in, no plasma flow problems, no critical mirror fabrication or aging problems, smaller number of parts, absence of mechanical moving parts (which makes them durable), and high resistance to environmental influences. These gyros are immune to electromagnetic interference and can withstand large accelerations (42). An excellent treatment of the features, advantages, and disadvantages of RLGs versus FOGs is provided by Udd (2).

Typical drift rates are 0.01 deg/h (3). One similarity between RLGs and FOGs is that in both it has been relatively easy to achieve low performance, but much research has been needed to improve the performance to 0.01 deg/h levels. FOGs have been replacing RLGs in many civil and military applications, especially those with less demanding drift rates of approximately 1 deg/h. Accuracy has been the main disadvantage of FOGs when compared with mechanical gyroscopes and RLGs. Within a few years, however, FOGs are expected to achieve comparable drift rates to RLGs. Target values for precision FOGs are 0.001 deg/h drift rate, 0.0005 deg/h$^{1/2}$ random walk, 5 ppm scale factor, and 500,000 h stability (51).

Miniaturized Gyroscopes on Chip. A number of products combining integrated optics and fiber optics have been developed recently. The cost of medium-performance FOGs of accuracy range 1 to 10 deg/h can be reduced by using an integrated optoelectronics module as the key component. The processes for fabricating the integrated optics components are similar to the batch processes used by the semiconductor industry to mass-produce integrated circuits. In addition, this technology allows the use of inexpensive telecommunications optical fiber for the fiber coils. Such systems comprise a light source, its driver, a detector, a filter, an ADC, and an integrated optics coupler. Typically, all of the optical components are integrated optics, except for the fiber coil, light source, and optical detector–preamplifier and depolarizers.

The coils are mounted on a chassis along with the other components. The light source is typically a superluminiscent diode or an edge-emitting LED, similar to those used in short-range telecommunications. These light sources have short coherence lengths and can be efficiently coupled into the core of a single-mode fiber. The low coherence is important for minimizing optical reflections and other disturbances that can affect performance and reliabilty. The fiber-optic couplers (normally 2.5 to 5 cm) and a phase modulator (normally 0.6 to 2.5 cm), when integrated, fit on a 2.5 × 2.5 cm integrated optics chip.

These optoelectronic chips are available in single- dual-, and three-axis configurations for medium- and high-accuracy applications with bias performance in the 0.01 to 10 deg/h range. If the gyro is multiaxial, many of the optical and electrical components can be time-shared between the axes, resulting in significant reductions in cost, size, weight, volume, and number of parts. For example, a single chip is produced that allows all gyros to share a single laser diode, eliminating the need for three separate laser diodes. The reduction in the number of parts has the additional benefit of operation without mechanical gyro errors. An all-fiber gyro is less accurate than a fiber–integrated-optics gyro.

Many such devices incorporate intelligence on chip, and employ application-specific integrated circuits (ASIC) for operation, eliminating the need for a digital-to-analog converter (DAC). On-board processors take care of data handling, temperature compensation, scaling, and filtering. Such a chip can be designed with an operating wavelength between 630 and 3200 nm.

Optoelectronic gyroscopes can give rate outputs for angular accelerations up to 300,000 deg/s^2 and can withstand 30g shocks from six directions. Typical packaging volume is 100 cm^3, and typical power consumption is 2 W.

In 1993, Hitachi Cable developed a business-card-size FOG, which integrates an optical coupler, polarizer, detector, and other components into an optical integrated circuit chip (52). The integrated circuit comprises a Y-branch glass optical waveguide and two phase-shift modulators. It connects a signal-processing circuit, sensing coils, and a fiber coupler to make up the phase-shift modulation gyro. The device is mainly used in car navigation systems and costs less than 10,000 Japanese yen.

Another device by Hitachi, named GyroAce V, which measures 80 × 80 × 35 mm, is an analog-output gyro that uses a polarization surface protection optical fiber, which is not affected by temperature and vibration. The response speed of the device is 1 ms, the operating temperature ranges from −30 to 75 °C, and the price is about 200,000 Japanese yen.

The trend of the technology is towards greater integration, resulting in a gyro on chip in which the sensing element and the electronics to analyze it will be included in a single piece of silicon of size 1 cm^2, mass-produced with very low cost. One problem is the development of pigtailing techniques (procedures to connect fiber to the integrated chip). This is challenging due to the alignment required. It is particularly important for higher-accuracy (0.01 deg/h) FOGs. When polarization-maintaining fibers are employed, the major axes of these fibers need to be precision-aligned with the polarization axis of the waveguide and the light source.

Nuclear Magnetic Resonance Gyroscopes

Certain particles such as electrons, protons, neutrons, and nuclei intrinsically possess angular momentum. Employing this angular momentum as the basis for a gyroscope has long been considered, and such instruments have been suggested (53). All approaches suggested so far are based on nuclear magnetic resonance (NMR), where a net nuclear magnetization is established by some means (54).

The precession of the net nuclear angular momentum is observed in an applied magnetic field H_0, from which rotation information is deduced. The frequency of precession about H_0 (the Larmor frequency) is proportional to the magnitude of H_0: $w_0 = \gamma H_0$. The constant γ characterizes the particle used. If the frame is rotating at an angular rate w_r, then the observed frequency will be shifted: $w = \gamma H_0 - w_r$. For typical values of w_r for a practical navigational gyro, use of this equation would require very precise knowledge of H_0.

Using two particles with different spins in the same magnetic field, two different Larmor frequencies w_1 and w_2 can be observed. The two unknowns, the magnetic field and the rate of rotation, can be found by solving the following pair of equations:

$$w_1 = \gamma_1 H_0 - w_r \tag{13}$$

$$w_2 = \gamma_2 H_0 - w_r \tag{14}$$

Any method based on these equations relies upon the constancy and knowledge of the gyromagnetic ratios γ_1/γ_2. This dependence can be eliminated by the use of two magnetic fields in opposite directions and a resonance cell containing both kinds of nuclei in each magnetic field (5).

Factors characterizing the performance of an MRG are noise on the angle output, angle random walk, and bias effects. The drift rate is approximately a few hundredths of a degree per hour. Research on the development of this type of gyro is ongoing (55,56).

APPLICATIONS

Ships and Aircraft

Gyrocompass. A gyrocompass is an instrument that is used in ship or aircraft navigation to provide a fixed reference direction by pointing toward true or geographic north. The device is basically a special configuration of the rate-integrating flywheel gyroscope, employing a gravity reference for the north-seeking function. A compensated magnetic compass indicates magnetic north, which is different than true north. A gyrocompass, however, when properly adjusted, can be made to indicate true north. A gyrocompass is more reliable than a magnetic compass because it is not affected by magnetic disturbances such as those due to the steel hull of a ship. The gyrocompass is not dependent on the magnetic field of the earth and should not be confused with gyromagnetic compasses such as the Gyrosyn Compass described later.

Marine Gyrocompass. Almost every large ship carries at least one master gyrocompass installed in its own gyro room. An example is shown in Fig. 20. A transmission system links the master compass to *repeaters,* which are used on the ship for steering, positioning, and course recording. A marine gyroscope can take a number of different forms, all of which make use of the principle of the gyroscope and the pendulum. In its simplest form, the instrument consists of a rapidly spinning wheel, driven by a motor, and suspended so as to function as a pendulum and to respond to the earth's gravity. It is a three-frame gyroscope with its spin axis horizontal. As the earth rotates, the gyroscope finds an equilibrium position with its axis of spin parallel to the local meridian—that is, the axis assumes a north–south orientation. The gyrocompass incorporates damping features to control its motion as it aligns itself with the local meridian. It also needs to be compensated for the rolling, pitching and other motions of the ship on which it is placed.

Figure 20. MK 37 VT Digital Marine Gyrocompass by Sperry Marine Inc. (Photo courtesy of Sperry Marine Inc., Charlottesville, VA.)

In another form of a gyrocompass, a gimbal ring is attached to a support rod extending from the diameter of the ring. The axis of the spinning wheel and the support rod are perpendicular to each other. In most pendulum suspensions, a knife-edge is used as the top support point, restricting the motion of the pendulum and placing unwanted torques when a twist occurs. In this case, a ball floating in mercury is employed so that pendulum motion can take place freely in any vertical plane. This way, the support point can twist freely about a vertical line without placing an unwanted torque on the gyroscope pendulum.

In order to understand the north-seeking (or meridian-settling) property of the gyrocompass, consider a gyroscope at the equator whose axis is lying along the east–west direction. Since the gyroscope is supported as a pendulum, the support point, the center of mass of the gyroscope, and the center of the earth tend to lie along the same vertical line. However, as the earth rotates, the vertical line sweeps through space along the equator. The gyroscope cannot maintain its initial orientation due to gravitational forces. A torque, or twist, is impressed on the gyro, with the torque vector lying along the north–south direction. As soon as a tilt develops, the pendulum introduces torques that precess the spin axis towards the meridian and tries to align the gyroscope axis in the same direction as the torque. The gyroscope precesses from its original westward direction until its axis also points along a north–south direction. Depending on the amount of damping, it follows a spiral with an ever-decreasing radius. When stabilized, the spin axis is maintained in the meridian plane by a precession equal but opposite to the drift at the particular latitude. Once the alignment with the north–south direction is complete, the earth's rotation cannot impress any further torque on the gyro, because the torque cannot be transmitted through the bearings of the spinning wheel when in that direction. As the ship that carries the gyrocompass continues its motion, the torque redevelops and the gyroscope realigns itself with the local meridian. A gyrocompass functions at other latitudes besides the equator also, but only the motion of the component of the vertical line that is perpendicular to the earth's axis can impress a torque on the gyrocompass. When there is no tilting effect, the marine gyrocompass will lose its directional properties and become useless. This is the case at the poles of the earth, where the vertical line is parallel to the earth's axis and no torque can be transmitted to the instrument. Thus, the sensitivity of the gyrocompass is maximum at the equator and decreases to zero as the north or the south pole is approached. Also, when a vehicle moves to the west with a speed equal to the surface speed of the earth, the gyrocompass loses its sensitivity. This device cannot be used for air navigation because this condition can easily occur in the middle and upper latitudes.

Aircraft Gyrocompass. Aircraft gyrocompasses are almost always of the magnetic type, stabilized by a gyroscope. These are based on automatically monitored directional gyroscopes spinning on a horizontal axis, in which the monitoring device senses the direction of the meridian and ensures that the gyroscope axis is maintained in this direction, pointing towards the magnetic north pole.

Gyrosyn Compass is the tradename for a magnetic compass developed by Sperry Gyroscope Company and that came into use following World War II. Unlike an ordinary magnetic compass, it is driven electrically, and it adjusts more quickly to course changes of the aircraft. The monitoring device consists of a magnetic sensing unit, called the *flux valve,* which is mounted in the wing tip or some other remote location on the plane. Any relative change between the aircraft and the earth's magnetic field results in a voltage signal in the flux valve, making allowance for variation in the direction of the earth's magnetic field. This voltage signal is amplified electronically and applied to the gyroscope to keep it pointing towards magnetic north. The device can operate repeater compasses wherever they are needed in the aircraft.

Gyrostabilizer. When its rotor is very heavy, a gyroscope can function as an actuator: a device that directly controls a vehicle. The stiffness of the rotor is used to maintain the orientation of vehicles such as spacecraft, ocean ships, and automobiles. A gyrostabilizer is a large gyroscope that counteracts the rolling motion of a ship at sea and makes travel more comfortable. The device is mounted on pedestals bolted to the ship's framework. A self-contained electric motor drives the rotor. A number of ships and yachts built between World War I and World War II used gyrostabilizers, which accounted for about $1\frac{1}{2}\%$ of the entire weight of a ship. Such large gyroscopes, by themselves, are no longer used to stabilize ships, because they would have to be very large and heavy in order to control the large ships of today. The US Navy uses them only aboard Polaris missile-firing submarines.

Modern stabilizers make use of a set of fins controlled by gyroscopes as illustrated in Fig. 21. The fins extend out from the ship's hull and are operated so that the forward motion of the ship produces a tilt in one direction on one fin, and in the opposite direction on the other fin. The gyroscopes sense the vertical angular displacement and the roll velocity and provide the proper control for the fins to oppose the rolling motion caused by waves beating against the ship.

Gyropilot. The gyropilot, also called an automatic pilot or autopilot, is a device which automatically steers ships or aircraft closer to a course than a human helmsman or pilot can. The gyropilot allows more accurate navigation and economical operation. If autopiloting can be done very accurately and reliably, unmanned aerial vehicles or ships can be realized. An autopilot uses the artificial horizon and the gyrocompass to operate the mechanisms controlling the rudder, elevators, and ailerons, thus allowing the craft to fly long distances without a human pilot.

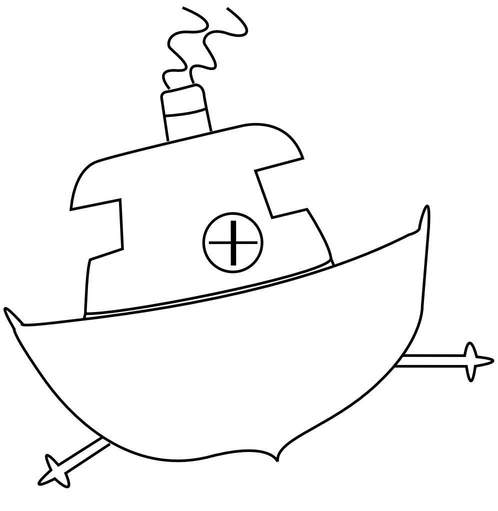

Figure 21. A ship stabilizer with fins controlled by a gyroscope. The gyroscope is unaffected by the rolling motion of the ship. It controls the pitch of the stabilizing vanes that counteract the rolling.

In modern gyropilots, rate detection is the principal reference, and displacement detection plays a secondary role. Basically, the gyropilot consists of three devices. Each device detects deviations of the aircraft from its proper course and attitude in one plane and generates a corrective signal to correct for the disturbances. The corrective signals are voltage displacements, which are amplified and sent to servo units, which have small electric motors that move the aircraft's controls. The controls are: rudder control for azimuth and sudden change in heading disturbances (yaw), aileron control for roll disturbance, and elevator control for pitch disturbance. First, corrective rudder control is applied to the rudder servomotor. The roll disturbance is detected by a roll gate gyroscope and a roll angle pendulum, which senses displacement. The aileron servo applies corrective action. Pitch disturbance is detected by a pitch rate gyroscope and a pitch pendulum. The elevator servo also applies corrective action.

The gyropilot for ships controls the rudder according to corrective signals from a gyrocompass. The first automatic pilot for ships was used in the early 1920s. The automatic pilot aboard ships is often called "iron mike" or the "iron quartermaster."

Other Aircraft Instruments. In aircraft, gyroscopes are used in several other instruments which are either part of the autopilot or are used for visual reference. The three primary gyroscopic instruments fitted to the flight panel are a rate-of-turn indicator (or turn-and-bank indicator), which is simply a rate gyro; a directional gyroscope; and an artificial horizon. These gyros may be driven either by electric motors or by air jets.

The directional gyroscope forms a standard reference for the pilot and navigator, indicating in what direction the aircraft is heading. It is a three-frame gyroscope with its spin axis on the horizontal plane. As soon as tilt develops, a switch is closed between the gyroscope housing and the vertical gimbal ring, and a motor introduces a torque in the horizontal plane that causes the gyroscope to precess back toward the horizontal.

The artificial horizon, or horizon indicator, indicates the orientation of the aircraft relative to the horizon and displays the rolling and pitching motion of the aircraft, without the pilot's having to look at the ground or horizon. It consists of a three-frame gyroscope with its spin axis vertical, and automatic correcting devices to counteract the apparent motion of the spin axis around the celestial pole and any other random precessions.

Inertial Navigation (Guidance) Systems. One of the most important uses of the gyroscope is in INSs for aircraft, spacecraft, or military equipment. These depend on the inertia of an extremely precise gyroscope to keep the craft traveling in exactly the right direction. Gyroscopes are the primary source of navigation and guidance information on spacecraft, since magnetic compasses are useless in outer space and there is no local horizon to sight on. Gyros are also used to accomplish the orientation control of the accelerometers, which are key components of INSs. INSs are nonradiating, nonjammable, dead-reckoning systems.

When INSs emerged for civil aviation in the 1970s, they were so large, heavy, expensive, and costly to maintain that they were used only on very large transoceanic transports. In the early 1980s, smaller, lighter, more reliable RLG-type gyroscopes were developed, and the civil market was expanded to a greater number of potential applications such as inertial navigation of larger business aircraft.

Modern INSs require a small platform very accurately stabilized by gyroscopes. This type of platform was perfected only in the 1950s after advances in the design of air-supported bearings and flotation gyroscopes. The inertial platform is extremely small and must be stabilized to an extraordinary degree of precision. The two types of self-contained INSs are the *gimbaled* INS and the *strapdown* INS. In a gimbaled system, the gyros and accelerometers are isolated from the rotations of the vehicle so that they can be maintained in a specific orientation with respect to the earth or inertial space. The stabilized INS physically represents the inertial reference frame. This greatly simplifies the position and velocity computations and reduces the dynamic-range requirements on the gyros. In a strapdown INS, the gyros measure the full rotation rates of the aircraft and keep track of the instantaneous orientation of the accelerometers in order to properly integrate the accelerations into velocity and position. This is done by applying control torques to the gyros, causing them to precess at precisely the same rate as the combination of the earth's rate of rotation plus the angular rate of the vehicle's position with respect to the earth. This way, two of the accelerometers are locally leveled, and the third one is kept vertical at all times. Since computation of a reference attitude matrix is required, strapdown INSs were made possible only by the advent of small and speedy digital computers (3). Most of the modern aircraft and marine INSs today are of the strapdown type. The errors caused by vehicle maneuvers and accelerations can be larger in strapdown systems. For gimbal systems, the typical gyro drift rate is 0.01 deg/h; for strapdown systems, the error is 20 to 50% worse.

If single-degree-of-freedom gyros are to be used, three mutually orthogonal gyros are required for the north, east, and vertical coordinates. If two-degree-of-freedom gyros are to be used, only two gyros need be installed. The types of gyros currently found in INSs include floated rate-integrating gyros, electrostatically supported gyros, dynamically tuned rotor gyros, and RLGs (57).

Military

Gyroscopes have also been exploited for military applications such as guiding and controlling the automatic steering mechanisms of torpedoes, missiles, and projectiles, and smart and terminally guided or precision-guided munitions for large-caliber guns (or field artillery) on tanks and howitzers. Gyroscopes are also employed underwater to steer torpedoes toward the target regardless of underwater conditions.

Many of the most accurate long-range missiles are steered by INSs using gyroscopes. Conventional three-frame gyroscopes are used in ballistic missiles for automatic steering together with two-frame gyroscopes to correct turn and pitch motion. German engineers made significant advances in this field during the 1930s, and their knowledge was later used in the design of guidance systems for the V-1 flying bomb, a pilotless aircraft, and the V-2 rocket, an early ballistic missile. Most tactical-grade missile systems require an accuracy of 1 deg/h.

The ability of gyroscopes to define direction very accurately, when used in conjunction with sophisticated control mechanisms, led to the development of stabilized gunsights (or predictor sights), bombsights, antiaircraft systems, and platforms to carry guns and radar antennas on ships during World War II. The gyroscopic gunsight revolutionized aerial gunnery for jet fighter planes that automatically aim guns, rockets, and bombs. The method of stabilization used for gun platforms is essentially the same as the principle of stabilizing an inertial platform. The gyroscopes that detect platform displacement are not as accurate as the flotation type. The sight fitted on the gun contains a rate gyroscope capable of measuring angular velocities in two planes at right angles to each other. The gyroscope is a three-frame one constrained by horizontal and vertical springs to the inner and the outer gimbal, respectively. Sometimes, variable-strength magnetic fields are employed to constrain the rotor axle in azimuth and elevation instead of a mechanical spring arrangement. The field coils for producing the horizontal component of this magnetic field are coupled to the rangefinder. The current through the vertical coils is adjusted so that the field depends on the drop of the projectiles due to gravity. The sensitivity of the gyroscope in the horizontal plane is a function of the sighting range; in the vertical, it is a function of the gravity drop. In operating the gunsight, the gunner holds the image of a central dot over the target while the gun is automatically aimed by the gyroscope at the predicted target position when the projectile motion is completed. This way, correct aiming to direct antiaircraft guns, guns of warships, and bombs to moving targets is provided.

Automotive

Among the automotive applications of gyroscopes are antiskid braking systems for vehicles and active suspension systems. In antiskid braking systems, a single-axis yaw-rate gyroscope senses any tendency of the vehicle to spin and sends signals to the braking and steering systems to prevent skidding (20). In active suspension systems, the springs and shock absorbers of conventional suspensions are replaced with computer-controlled hydraulic units for dynamic ride control. Gyroscopes find use in such systems as yaw-rate units to provide rate data, as well as instrumenting the vehicles for crash studies.

Robotics

Control of robotic tools in space by robot arms, machine control, development of autonomous warehouse and factory robotic systems and mobile platforms, as well as rough-terrain navigation, are some of the applications that immediately come to mind.

A number of robotic systems have been described which use some form of absolute sensing mechanisms for guidance (see Ref. 5 or 58 for surveys). Such systems typically rely on the availability of easy-to-see beacons or landmarks, using simple encoder information to predict vehicle location between sensing locations. This works well when the density of beacons or landmarks is high and the ground over which the vehicle travels is smooth. In cases where the beacon density is sparse or the ground is uneven, such systems can easily lose track of their position. This is particularly a problem for vehicles operating in outdoor environments. INSs can potentially overcome this problem. Inertial information can be used to generate estimates of position over significant periods of time independent of landmark visibility and the validity of encoder information. Clearly, positions derived from INS must occasionally be realigned using landmark information, but a system that combines both inertial and landmark sensing can cope with substantially lower landmark density and can also deal with terrain where encoder information has limited value.

INSs have been widely used in aerospace applications (5,59,60) and have been only recently exploited in robotics applications, where they have considerable potential. In work reported in Ref. 61, inertial sensors were used to estimate the attitude of a mobile robot. With a three-gyro, two-accelerometer configuration, experiments were performed to estimate the roll and pitch of the robot when one wheel climbs onto a plank using a small inclined plane.

One reason that INSs are widely used in aerospace applications but not as much in robotics is simply that high-quality aerospace inertial systems are too expensive for most robotics systems. However, low-cost solid-state INSs, motivated by the needs of the automotive industry, are increasingly being made available commercially. Although a considerable improvement on past systems, they clearly provide substantially less accurate position information than equivalent aerospace systems. However, such systems are at a point where, by developing reasonably detailed models of the inertial platform, they can provide valuable information in many robot positioning tasks (25,62). An inexpensive INS developed for a mobile robot platform is illustrated in Fig. 22.

Figure 22. A low-cost INS comprising three gyroscopes, a triaxial accelerometer and two tilt sensors, developed for a mobile robot platform. (See B. Barshan and H. F. Durrant-Whyte, *IEEE Trans. Robot. Automa.* **11** (3), 328–342, June 1995. Copyright IEEE, 1995.)

In a robotics context, the primary motivation has been the need to develop a system capable of providing low-cost, high-precision, short-time-duration position information for large outdoor automated vehicles and mobile platforms. In particular, the interest has been in obtaining location information for short periods when the vehicle is not in contact with any beacon or landmark information. Rough terrain, variations in wheel radius, tire slip, and body deflection cause the encoder information to be unreliable for location estimation except over very short sample intervals. Inertial sensing offers a potential solution to this type of problem.

Positioning Systems

Another system that is potentially of great value for vehicle localization is the global positioning system (GPS) (63). It is a satellite-based radio navigation system that allows a properly equipped user access to useful and accurate positioning information anywhere on the globe. The fact that an absolute identification signal, rather than a direct measurement of range or bearing, is used to compute location means that measurements are largely independent of local distortion effects. The position accuracy that can be achieved with GPS in 5 m in the military band, and 50 m in the civilian band. However, using a technique known as differential GPS, in which a separate base receiver is employed, civilian accuracy may be improved to 5 m. Although this is not as good as can be achieved using high-frequency radar, it may still be adequate for some applications. It is also worth noting that the cost of GPS receivers is remarkably low (about $1000). In Ref. 64, integration of GPS with INS is described for precision navigation in aerospace applications. The cost of these hybrid systems has been considerably reduced due to the dramatic drop in the cost of GPSs, the expected mass-production cost being $15,000, about one-third the price of a comparable system using RLGs.

A hybrid INS–GPS offers important benefits, especially for military applications. The accuracy required of an INS can be relaxed significantly when used in combination with a GPS receiver. Overall system performance can be improved by fusing INS data with GPS signals to correct for inertial drift errors. Although GPS offers higher accuracy, most military planners would not want to rely solely on GPS, since the GPS satellites can be attacked by the enemy and the received signals are vulnerable to short-term interference and jamming, unlike INS. The possibility of jamming increases the requirement for inertial accuracy. For weapons, in the event that the GPS were jammed after launch, the INS must be sufficiently accurate to complete the task by itself. Many hybrid INS–GPS systems need the INS for short signal blockages that occur during aircraft maneuvering, and for navigation through clutter or adverse weather conditions. As an example, an augmented GPS-based system outfitted with 0.1 deg/h FOGs can tolerate a loss of GPS signals for 10 min and still arrive within 30 m of its intended target (12).

Although GPS is excellent for navigation, it does not sense dynamic changes rapidly enough for air vehicle flight control systems. GPS provides location data but not in real time, since it relies on satellite transmission received at certain intervals. During the gaps between satellite updates, localization by GPS is impossible.

Development of such accurate positioning systems would allow unmanned autonomous transport vehicles, seekers, and intelligent-vehicle highway systems for land navigation (65). More widespread installation of hybrid INS–GPS systems on emergency vehicles such as police cars, ambulances, and fire engines is expected in the near future.

Industry and Mining

Gyros suitable for surveying tasks were developed in Germany between 1947 and 1949. Later, the instruments were improved for practical applications. Road mappers and surveyors find gyroscopes useful in recording curves and grades. Wellbore-logging systems in oil and gas exploration have used gyroscopic devices to control the orientation of the shaft to ensure that the drilling is performed in the correct direction (66). Survey gyros are mainly employed for geodesy, subterraneous geometry, surveying tunnels and boreholes in underground mine exploration, and shield excavators used in tunnel construction. Frequently, the rate gyros or gyrocompasses are designed to allow the fitting of optical measuring instruments or to allow combination with a theodolite (gyro theodolite). In these applications, gyrocompasses are preferred, since magnetic compasses would be disturbed by metal deposits. Ligament-suspended surveying gyros attain accuracies of one minute of arc within about 2 to 5 min in the absence of disturbances (57).

Other Applications

Vertical three-frame gyros with pen recorder attachments are often used to analyze rolling and pitching movements of ships and rocking motions of trains and to record the conditions of railroad tracks. With a very accurate gyro, almost every fault in the level of tracks can be detected. Other motion measurement systems that employ gyroscopes are those used in sports training or at remote buoys for long-term recording of wave motion.

Gyroscopes are utilized as steadiers, stabilizers, and jitter/motion compensators for equipment such as hand-held video camcorders, ground cameras, lenses in satellites, binoculars, and other optical instruments. On the larger scale, gyroscopes are used to stabilize and compensate for the random motion of millimeter-wave seekers in long-range rocket systems, communication or shipboard satellites, radar-tracking antennas, antennas on remotely piloted vehicles, and weapon platforms. They are also used for the stabilization of the line of sight in various instruments.

Geophysical applications include measurement of the earth's rotation, continental drift, and earthquakes. A recent example is a Zerodur glass RLG manufactured by Carl Zeiss (67). This gyro is capable of achieving a relative resolution of 0.1 ppm over long periods of time. This allows high accuracy in determining the fluctuations in the earth's rotation, which is of importance to geophysicists who use such fluctuations to study the earth's interior structure, continental drift, and the occurrence of earthquakes. A 1.2 × 1.2 m block of Zerodur glass with a thickness of 180 mm and a weight of approximately 600 kg comprises the body of the RLG. The use of Zerodur stabilizes the length of the laser beam path and guarantees the required measuring accuracy by virtue of the nearly zero thermal expansion coefficient of the material. Inside the Zerodur block, there are four 1 m long longitudinal bores for the laser beam. A closed square resonator is produced by four deflecting mirrors fitted at each of the corners of the block. The principle of operation is otherwise the same as other RLGs. The gyro is installed in a subterranean cave on the Banks Peninsula in New Zealand.

Another device for measuring the rotation of the earth, a superfluid gyroscope designed like an ac superconducting quantum interference device (SQUID), has been demonstrated by R. Packard and his colleagues at the University of California, Berkeley. In their demonstration, the metrologists measured earth's rotation with a precision of 0.5% (68). In a superfluid, fluid circulation is quantized, which can be exploited to measure tiny rotations. In the Berkeley experiment, the flow of superfluid helium through a ring-shaped vessel is interrupted by a very thin barrier containing a sub-μm-sized pinhole. When the vessel is rotated, the helium must squirt back through the hole to maintain constant circulation in space. By monitoring the squirting, it is possible to measure the rotation of the earth.

Researchers at Stanford University and NASA have developed an experiment, known as Gravity Probe B, involving very precise gyroscopes for testing two unverified predictions of Albert Einstein's general theory of relativity (69–71). The experiment is based on measuring how space and time are affected by the presence of the earth ("the geodetic effect"), and how the earth's rotation drags space-time around with it ("frame dragging"). These effects are detected by precisely measuring tiny changes in the direction of spin of four gyroscopes. The gyroscopes will be contained in an earth satellite orbiting at an altitude of 400 miles directly over the poles. Since the gyroscopes are free from any disturbance, they provide an almost perfect space–time reference system.

Gyroscopes have also found some applications in medicine. The alignment and rotational motion-sensing properties of gyros can be used for diverse medical applications such as precise positioning of surgical instruments, analyzing back motions for orthopedic diagnosis, orthotics, and prosthetics, and measurement of human movement and diagnosis of motion disorders. For example, measuring the tremors associated with Parkinson's disease aids in diagnosis and treatment of the disease.

Enhanced pointing technology for computers has been developed in the form of a three-dimensional mouse equipped with a very small gyroscope (the GyroEngine), which is no longer restricted to the desktop and can be operated in free space (72,73). This is useful for three-dimensional applications such as airplane design.

Other miscellaneous applications include flight simulators, flight training systems, measurement of wave motion, and development of smart tools such as carpenter's levels for instrumentation.

Ref. 74 provides a detailed literature and patent survey on gyroscopes and their applications.

FUTURE TRENDS

Current gyro technology is progressing along several fronts. On one front, traditional spinning gyros are made smaller, lighter, and more reliable. In some cases, optics is integrated with mechanics, resulting in optomechanical gyroscopes. However, new types of gyroscopes with no moving parts have greater potential importance. Conventional flywheel gyroscopes are being replaced by solid-state gyroscopes with no moving parts that are smaller, less expensive, more versatile, rugged, accurate, and reliable. Computer chips are replacing mechanical components, which wear out and are expensive to fabricate. Advances in optical fiber research and solid-state technology have a direct impact on the development of modern gyroscopes. It is expected that by the turn of the century, gyroscopes will be more widely used in the control systems of automobiles, trucks, and emergency vehicles, among many other applications.

BIBLIOGRAPHY

1. I. Cochin (ed.), *Analysis and Design of the Gyroscope for Inertial Guidance,* New York: Wiley, 1963.
2. E. Udd (ed.), *Fiber Optic Sensors Based on the Sagnac Interferometer and Passive Ring Resonator,* New York: Wiley, 1991, pp. 233–269.
3. C. Lin, *Modern Navigation, Guidance, and Control Processing,* Englewood Cliffs, NJ: Prentice Hall, 1991.
4. Anonymous, DARPA boosts interferometric fiber-optic gyros, *Opt. Mater. and Eng. News,* **1** (7): Mar. 1991.
5. M. M. Kuritsky and M. S. Goldstein (eds.), Inertial navigation, in I. J. Cox and G. T. Wilfong (ed.), *Autonomous Robot Vehicles,* New York: Springer-Verlag, 1990.
6. E. F. Carter (ed.), *Dictionary of Inventions and Discoveries.* New York: Crane, Russak, 1966.
7. G. M. Sagnac, L'éther lumineux démontré par l'effet du vent relatif d'éther dans un interféromètre en rotation uniforme, *C. R. Acad. Sci.* **95**: 708–710, 1913.
8. G. J. Martin, Gyroscopes may cease spinning, *IEEE Spectrum,* February 1986, pp. 48–53.
9. Merton Allen Associates, Design, uses, and performance of fiber optic gyroscopes, technical report 1, Merton Allen Associates, Silver Spring, MD, January 1997.
10. V. Vaili and R. W. Shorthill, Fiber ring interferometer, *Appl. Opt.,* **15**: 1099–1100, 1976.
11. P. J. Klass, Fiber-optic gyros now challenging laser gyros, *Aviation Week & Space Technol.,* **145** (1): 62, July 1996.
12. M. K. Reunert, Fiber optic gyroscopes: Principles and applications, *Sensors,* August 1993, pp. 37–38.
13. J. Fraden (ed.), *AIP Handbook of Modern Sensors,* New York: Amer. Inst. of Physics, 1993.
14. Anonymous, Injection-molded optical gyroscope offers cost, size, weight, savings, *Aviation Week & Space Technol.,* **135** (16): 100, October 1991.
15. Anonymous, New miniature gyroscope developed using optical sensors, *Opt. Materials and Eng. News,* **2** (3): November 1991.
16. B. D. Nordwall, Quartz fork technology may replace INS gyros, *Aviation Week & Space Technol.,* **140** (17): 50, April 1995.
17. S. D. Orlosky and H. D. Morris, A Quartz Rotational Rate Sensor, *Sensors,* February 1995.
18. Vital Information Publications, Sensor markets and technologies update: microminiature solid state quartz gyro is tuned into growth applications, *Sensor Bus. Dig.* **2** (12): September 1993.
19. Anonymous, New quartz IMUs may challenge fiber optic gyro market, *Mil. and Commerical Fiber Business,* **7** (19): September 1992.
20. T. Shelley and J. Barrett, Vibrating gyro to keep cars on route. Eureka on campus, *Eng. Materials and Design,* **4** (2): 17, Spring 1992.
21. B. Dance, Piezoelectric ceramic elements from compact gyroscope, *Design News,* September 20, 1993, pp. 113–115.
22. S. Fujishima, T. Nakamura, and K. Fujimoto, Piezoelectric vibratory gyroscope using flexural vibration of a triangular bar. In *Proc. Frequency Control Symp.,* 29 May 1991.
23. Murata, Gyrostar piezoelectric vibrating gyroscope (product literature), Smyrna, GA: Murata Electronics North America, 1994.
24. Murata, Gyrostar piezoelectric vibrating gyroscope: Test and reliability data (technical manual, catalog no. T-03-B), Smyrna, GA: Murata Electronics North America, 1994.
25. B. Barshan and H. F. Durrant-Whyte, Evaluation of a solid-state gyroscope for robotics applications, *IEEE Trans. Instrum. Meas.,* **44**: 61–67, 1995.
26. E. O. Schulz-DuBois, Alternative interpretation of rotation rate sensing by ring laser, *IEEE J. Quantum Electronics,* **QE-2**: 299–305, 1996.
27. W. W. Chow et al., The ring laser gyro, *Rev. Modern Phys.,* **57** (1): 61–104, January 1985.
28. J. G. Koper, A three-axis ring laser gyroscope, *Sensors,* March 1987, pp. 8–21.
29. S. Chao, W. L. Lim, and J. A. Hammond, Lock-in growth in a ring laser gyro, In *Proc. Physics and Optical Ring Gyros Conf.,* Snowbird, UT, January 1984, Proc. SPIE 487, pp. 50–57.
30. N. Buholz and M. Chodorow, Acoustic wave amplitude modulation of a multimode ring laser, *IEEE J. Quantum Electronics,* **QE-3**: 454–459, 1967.
31. J. Chesnoy, Picosecond gyrolaser, *Opt. Lett.,* **14** (18): 990–992, September 1989.
32. W. R. Christian and M. J. Rosker, Picosecond pulsed diode ring laser gyroscope, *Opt. Lett.,* **16** (20): 1587–1589, October 1991.
33. M. L. Dennis, J. M. Diels, and M. Lai, Femtosecond ring dye laser: A potential new laser gyro, *Opt. Lett.,* **16** (7): 529–531, April 1991.
34. Fiber optic rotation sensors and related technologies, in S. Ezekiel and H. J. Arditty (ed.), *Proc. First Int. Conf., MIT,* Springer-Verlag: New York, 1982.
35. F. Aronowitz, *The Ring Laser Gyro, Vol. 1,* New York: Academic Press, 1971.
36. L. N. Menegozzi and W. E. Lamb, Theory of a ring laser, *Phys. Rev. A,* **1** (4): 2103–2125, October 1973.
37. J. R. Wilkinson, *Ring Lasers, Vol. 11,* Pergamon Press, Oxford, UK, 1987.
38. G. A. Sanders, Critical review of resonator fiber optic gyroscope technology, in E. Udd (ed.), CR44, SPIE Opt. Eng. Press, Bellingham, WA, September 1992.
39. S. Tai et al., All-fibre gyroscope using depolarized superluminiscent diode, *Electron. Lett.,* **22**: 546, 1986.
40. H. C. Lefevre, The interferometric fiber-optic gyroscope, in E. Udd (ed.), CR44, SPIE Optical Engineering Press, Bellingham, WA, September 1992.
41. D. A. Nolan, P. E. Blaszyk, and E. Udd, Optical fibers, in Ref. 2, pp. 9–36.
42. P. J. Klass, New device cuts cost of fiber-optic gyros, *Aviation Week & Space Technol.,* **145** (20): 62, November 1996.
43. P. Adrian, Technical advances in fiber-optic sensors: Theory and applications, *Sensors,* September 1991, pp. 23–45.
44. H. R. Everett, *Sensors for Mobile Robots,* Wellesley, MA: AK Peters, 1995.
45. Hitachi, Fiber optic gyroscope (HOFG-1), specification SP 94-28-1005, Tokyo: Hitachi Cable, Ltd., August 1994.
46. Hitachi, Fiber optic gyroscope (HGA-D), specification SP 94-28-1006, Tokyo: Hitachi Cable, Ltd., August 1994.

47. Anonymous, Andrew launches fiber gyro-based land navigation system, *Sensor Business Digest,* **5** (8): June 1996.
48. S. Emge et al., Reduced Minimum Configuration Fiber Optic Gyro for Land Navigation Applications, *Proceedings of Fiber Optic Gyros: 20th anniversary conference* (SPIE): Denver, CO, August 5–6, 1996.
49. S. Bennett, S. R. Emge, and R. B. Dyott, Fiber optic gyros for robotics, *Service Robot: An Int. J.* **2** (4): 1996.
50. J. Blake et al., Design, development, and test of a 3-inch open loop all fiber gyro, in *Proc. 14th Biennial Guidance Test Symp.,* MSD-TR-89-21, Holloman AFB, NM, October 1989, 255–266.
51. Pasha Publications, Inc., Fiber optic gyro, *Defense and Aerospace Electron.,* **3** (44): November 1993.
52. Anonymous, Hitachi Cable develops business card-size optical fiber gyro, *Hitachi Weekly,* 9 (46), November 1993.
53. J. H. Simpson, *Electron. Lett.,* **2**: 42, October 1964.
54. B. Cagnac, *Ann. Phys.,* **6**: 1961.
55. P. Harle, G. Wackerle, and M. Mehnng, A Nuclear-Spin Based Rotation Sensor using Optical Polarization and Detection Methods, *Appl. Magn. Res.,* **5** (2): 207–220, 1993.
56. S. Appelt, G. Wackerle, and M. Mehnng, Deviation from Berry Adiabatic Geometric Phase in a XE-131 Nuclear Gyroscope, *Phys. Rev. Lett.,* **72** (25): 3921–3924, 1994.
57. R. S. Sindlinger, North-seeking gyros and their application for land vehicle navigation, lecture at the Carl Cranz Course, "Principles and Performance of Mechanical and Optical Inertial Sensors, Intertial and Satellite Navigation Systems," Braunschweig, Germany, October 1992.
58. J. J. Leonard and H. F. Durrant-Whyte, *Directed Sonar Navigation,* London: Kluwer Academic, 1992.
59. C. T. Leondes (ed.), *Theory and Applications of Kalman Filtering,* London: Technical Editing and Reproduction, 1970.
60. D. A. Mackenzie, *Inventing Accuracy: A Historical Sociology of Nuclear Missile Guidance,* Cambridge, MA: MIT Press, 1990.
61. J. Vaganay and M. J. Aldon, Attitude estimation for a vehicle using inertial sensors, in D. Charnley (ed.), *Preprints of the 1st IFAC International Workshop on Intelligent Autonomous Vehicles, Southampton, Hampshire, U.K.,* Pergamon, 1993, pp. 89–94.
62. B. Barshan and H. F. Durrant-Whyte, Inertial navigation systems for mobile roots, *IEEE Trans. Robot. Autom.,* **11**: 328–342, 1995.
63. B. W. Parkinson and S. W. Gilbert, Navstar: Global positioning system—ten years later, *Proc. IEEE,* **71**: 1117–1186, 1983.
64. B. Tiemeyer and S. Vieweg, GPS/INS integration for precision navigation, technical report, Institute of Flight Guidance and Control, Technical University of Braunschweig, Hans-Sommer-Str. 66, D-3300 Braunschweig, Germany, 1992.
65. Anonymous, Vehicle navigation drives opportunities for fiber gyros, *Sensor Business Digest,* **5** (1): 1995.
66. Anonymous, Fiber optic gyros for wellbore logging, *Enhanced Energy Recovery & Refining News,* **18** (8): March 1995.
67. Anonymous, Carl Zeiss Makes Ring Laser Gyro for Measuring Continental Drift, *EuroPhotonics,* Laurin Publishing Co., Inc., February/March 1997, p. 15.
68. K. Schwab, N. Bruckner, and R. E. Packard, Detection of the earth's rotation using superfluid phase coherence. *Nature,* **386** (6625): 585–587, April 1997.
69. G. Taubs, The Gravity Probe, *Discover,* **18** (3): 62–71, March 1997.
70. B. Ianotta, Music of the Spheres, *New Scientist,* 28–31, August 1996.
71. A. Lawler, Earthly Politics Boosts Space Probe, *Science,* **267**: 1756–1758, March 1995.
72. Business Communications Company, Inc., New miniature gyroscope developed using optical sensors, *Optical Mater. Eng. News,* **2** (3): November 1991.
73. S. W. Bhargava, Putting a new spin on the gyroscope, *Business Week,* **1** (3228): 1401, November 1991.
74. F. W. Cousins, The anatomy of the gyroscope: a report in three parts comprising a literature and patent survey directed to the gyroscope and its applications, in J. L. Hollington, (ed.), Technical Report AGARDograph Series No: 313, NATO Advisory Group for Aerospace Research and Development, 1988.

BILLUR BARSHAN
Bilkent University