conversion and storage module and a power supply. The array of accelerometers is firmly attached to the vehicle and the defined measurement sequence is undertaken. It is necessary to ensure that the attachment of the sensors does not modify the natural response of the vehicle, so it is normal to apply strips of aluminium tape to the object at the various locations being ‘sensed’. The accelerometers can then be fixed into position using an epoxy glue; an example of a triple-axis sensor suitable for use in a measurement campaign, is shown in Figure 15.28.

### 15.6 Geodetic and geophysical measurements and observation of fundamental physical phenomena

An accurate model of the shape of the Earth is a very important aspect of any terrestrial navigation system, as has already been discussed in Chapter 3. However, fluctuations in the rotational characteristics of the Earth also have an impact on the potential accuracy of terrestrial navigation systems, including those that use precision GPS data. Measurement of other changes to the behaviour of the Earth may be used to predict seismic events, such as earthquakes.

Many factors produce small fluctuations in the characteristics of the Earth’s rotational parameters. The principal factors that induce these fluctuations are;

- continental drift;
- motion of the moon and its phases;
- movement of the subterranean magma in the Earth’s core;
- tides;
- weather.

Chapter 13 and Appendix D considers the operation and use of the popular satellite-based navigation systems, which offer the potential for high-precision navigation for all types of vehicles and platforms. The basis of the technique is the constellation of satellites in geo-stationary orbits locked in a particular known position above the Earth. Consequently, errors in the estimated position of a navigation
Figure 15.29 Scale of factors perturbing RLG measurements

The system's receiver will occur owing to the displacement of the constellation of satellites, resulting from the fluctuations of the Earth's rotational motion. Hence, changes in these characteristics of the motion of the Earth need to be measured and understood, so that an appropriate compensation technique can be applied.

One technique that is being investigated for the measurement and monitoring of the Earth's rotation fluctuations involves the use of a very large ring laser gyroscope. A ring laser gyroscope is capable of providing more information about its experience in the environment than merely the angular motion imparted to it, that is, it is potentially much more than a gyroscope. The main contribution to the Sagnac frequency detected by a stationary ring laser gyroscope is the Earth's rotation rate, provided the input axis is aligned with the rotation axis of the Earth. Very accurate ring laser gyroscopes are capable of measuring other effects that perturb the sensor and thus modify the Sagnac frequency. The scale of some of these effects is illustrated in the schematic diagram of Figure 15.29.

A research group at the University of Canterbury in New Zealand, in collaboration with others, has pioneered studies into these topics and exploited the properties of this type of device through the construction of very large ring laser gyroscopes [20]. Currently there is a project involving collaboration between this group and the German Federal Cartography and Geodesy Office in Frankfurt, Germany.

Measurements are made of the rotation rate of the Earth using very large ring laser gyroscopes, typically having a perimeter of many metres. The enclosed area for the prototype was $\approx 3.5 \, \text{m}^2$, but the latest one is $\approx 16 \, \text{m}^2$ and is known as the gross ring (G-ring), with an even larger device having an enclosed area of $367 \, \text{m}^2$ being commissioned, in this case the structure is made of basalt. The lasers in these sensors use the helium–neon ‘633 nm transition’ and the population inversion for this transition is created by a radio frequency source, which is carefully controlled.
to avoid unwanted laser-mode generation. Consequently, unwanted mode-pulling effects in the laser cavity are avoided.

Careful control of the backscatter from the mirrors, with a total optical loss in the part per million category, enables the cavity to be unlocked by use of the Earth's rotation \(7.293 \times 10^{-5}\) rad/s. These lasers combine very high cavity finesse, through low total reflection losses, and large enclosed area to give excellent frequency resolution of better than one part in \(3 \times 10^{21}\) and position accuracy of 300 prad, with the enhanced frequency resolution leading to sub-microhertz resolution of the beat frequency.

The Fourier transform of the output from the laser cavity gives a spectral line associated with the rotation of the Earth often termed 'the Earth line'. Analysis of this spectral line is used to monitor the impact of seismic waves and other events. This ability to make high-precision measurements of rotation rates has led to applications in geodesy.

At the heart of this latest measurement system is a 4.25 m diameter disc of zerodure low-expansion glass that is 25 cm thick and forms the stable ring laser cavity. The rate of expansion is quoted as 60 nm/°C change in temperature. The ‘G-ring’ is believed to be the largest and most accurate ring laser in the world [21]. Its enclosed area is 16 m² and consequently is about 1000 times more accurate than the RLGs used in commercial aircraft. A photograph of the large RLG is shown in Figure 15.30.

In order for these sensors to achieve the full potential of their performance these ring laser gyroscopes are located in a very carefully controlled environment, such as a cavern; the G-ring RLG is at the Wettzell facility at Kötzting in Germany, others are at Cashmere in New Zealand. The ‘G-ring’ sensor is mounted on a granite slab that is 60 cm thick and has a mass of 10 tonnes, all embedded in a concrete base in an under-ground laboratory. Moreover, the laser system is encapsulated in a steel tank.
with a sophisticated control system to minimise ambient temperature and pressure fluctuations, thus ensuring maximum measurement accuracy from the sensor.

Techniques have been developed to enable the use of these large RLGs for studying a number of geophysical effects; particularly those associated with earthquakes. Of particular interest is the relationship between the ground rotational effects in a seismic event and induced rotational effects in buildings as they are generally particularly vulnerable to this type of motion. There is particular interest in the frequency dependence of responses of buildings in the 0.2–30 Hz band [22]. The effect of seismic events is to induce frequency-modulated side bands, in the 0.2–1 Hz region, around the ‘Earth line’, which indicate the presence of rotational components associated with seismic events.

The ‘G-ring’ will be used for the measurement of short-term fluctuations of the Earth’s rotation rate, with periods in the range of hours to days. Periodic geophysical signals with periods of around one day and half a day have become visible in the time series of ring laser observations. These signals are introduced by variations in the orientation of the ring laser plane and currently limit the uncorrected sensor resolution to 2 parts in $10^8$ with respect to the Earth’s rotation rate.

A GEOSENSOR [21] is being established to measure earthquakes. The GEOSENSOR consists of:

- a large single-axis ring laser gyroscope;
- a conventional three-axis broadband seismometer;
- a tiltmeter to measure changes in the orientation of the ring laser gyroscope;
- GPS time receiver to provide the time reference for the data acquisition system;
- auxiliary equipment and instrumentation to monitor the performance of the ring laser gyroscope and other equipment.

Currently, a demonstration system is under construction at the geodetic observatory at the Fundamentalstation Wettzell in Bavaria, Germany.

Alternative approaches to the use of very accurate inertial sensors to measure imperfection in the Earth’s rotation rate include the use of radio telescopes that measure the fluctuation characteristics relative to a very distant inertially stable object such as a quasar. However, this measurement is complex and the measurements are dependent on a network of radio telescopes located around the world.

The large RLG has detected an Earth tide signal at the lunar tidal period of 12 h 25 min [23]. The amplitude of this signal is one-millionth of Earth’s rate $\approx 15 \times 10^{-6}$°/h. This effect confirms other observations with large ring interferometers. These measurements are made from the changes in the orientation of the sensor resulting directly from lunar tidal effects and atmospheric loading. The strong tidal effects result from ocean-induced loading near the location of the sensor. It is anticipated that the larger ring-laser sensor under construction, this device will enable other effects, such as atmospheric pressure fluctuations at a lower level to be detected. Moreover, the effects of polar motion are expected to be detected by the more sensitive devices.

The large RLGs have been proposed for study of other physical phenomena, such as time-reversal invariance, or both parity and time-parity symmetry. The large ring laser cavity lends itself to this type of study as its beat frequency detects any effects
that contribute differently to the clockwise and counter-clockwise propagating beams in its cavity [24].

Investigation of the Lense–Thirring field, or reference frame drag [25], is an example of using the very large ring laser gyroscopes to detect fundamental physical phenomena. This is a relativistic effect that involves the coupling of an electromagnetic field owing to gravity. Lense and Thirring [26] showed, from general relativity, that the local inertial frames near a rotating mass rotated relative to those at infinity. A very popular term for the Lense–Thirring effect is inertial-frame dragging. This effect is also touted as a particularly characteristic and direct manifestation of the graviomagnetic effects associated uniquely with general relativity.

A number of proposals are being developed to devise experiments that would enable the very large RLGs to be used to measure the Lense–Thirring effect. This involves defining a very large RLG in the reference frame of the stars to very high precision and involves extreme metrology to enable extremely precise definition of the ring laser area normal vector to be defined. This would require an optical stellar interferometer to be positioned very close to the sensor, to provide the requisite attitude of the sensor in inertial reference axes.

15.7 Other applications

A number of additional applications, not covered by the categories of system described in the preceding sections, are discussed in the following section.

15.7.1 Moving-map displays

The principle of a moving-map display is based on terrain referenced navigation techniques and centres on the correlation of inertial positional and attitude data with digitised stored-map data. It is used as an aid to aircrew, being particularly valuable when flying in poor visibility or at night.

At the heart of this type of system is a mass data store, which may comprise the following:

- the flight plan of the proposed route or mission, which would include waypoints, routeing and timing cues;
- hazard data that may include potential constraints or intelligence information for military applications, which could incorporate data about locations of known missile sites, current battle areas, as well information about obstructions, such as pylons, chimneys and masts;
- cultural and environmental data, including diurnal information, which would include location of bridges, railways, rivers and roads;
- elevation profile data.

The flow of information in the database for this system is illustrated in Figure 15.31.

The other vital element of this navigation aid is the IN system, which normally includes aiding of the vertical channel with a barometer, and a precision altimeter.
This type of system enables a measurement to be made of the aircraft height above the ground, thus creating a profile of the terrain below. The profile is formed by calculating the difference between the IN-indicated height and the height above ground measurement given by the altimeter, as shown in the Figure 15.32.

Comparison of the time-series profile with the terrain-profile information stored in the database enables the exact position of the navigation system to be determined. The position of the aircraft is usually superimposed at its identified position on the map. The map projection may move so that the terrain below the aircraft ‘travels’ with the aircraft; additionally the position of the aircraft symbol may be selected so
that it is at the correct position with respect to its actual position on the appropriate projected image. This is analogous to moving a window over a scene.

This type of display is very flexible so the scale of the image can be increased to enable additional detailed features to be included, or diminished (i.e. a zoom function) to provide a large-scale view. Modern computer processing and image processing algorithms allow vast flexibility in the variety of information on the projected map, such as natural cultural features. The superimposed cultural information can be based on feature vectors or alternatively from digitised aeronautical maps.

This application is also common in commercial aircraft where the IN system data, from the aircraft’s navigation system, are used to provide passengers with an update of progress on their journey, as part of the entertainment system. In this case far less precision is required, so a much simpler system can be implemented without the need for the recourse to precision terrain referenced navigation, to provide the appropriate reference. It is common for the system to add additional features or information such as:

- place names and destination;
- time to go and current time at destination and starting point;
- velocity and altitude of the aircraft;
- distance to go;
- flight path and orientation of the aircraft;
- culture of the land masses;
- shadow indicating night time.

In military applications, this approach may be used in automated mission planning and execution of tasks to reduce the workload of the crew.

Moving-map navigation systems are becoming a common accessory in motor vehicles. These are based on a ‘GPS’ receiver and stored database in a baseline system. A more accurate system is possible when the output signal from the vehicle’s odometer is used to aid the basic system, thus providing an integrated navigation system. Motor car navigation systems are considered in more detail in Section 15.4.3.

Recent developments of moving maps have seen a satellite navigation system (GPS) linked to a stored digital map and a Braille display on a computer to help visually impaired people. A commercially available product enables this class of navigation system to provide a number of types of aid, such as directions or a count down to junctions, a destination or points of interest. However, these types of device are limited to outdoor use, as the ‘GPS signals’ do not penetrate buildings.

A form of integrated system that combines motion and direction sensors with a satellite-based navigation system is being developed to help blind people navigate inside as well as outside buildings. In this case, the motion sensors are used when satellite-based navigation systems, such as GPS, are not available.

The motion sensor pack contains:

- a digital magnetic compass;
- a barometer;
- a gyroscope.
- an odometer (pedometer)
The motion data are used in conjunction with a pattern recognition algorithm to determine the characteristics of the user's step pattern. Dead-reckoning techniques (see Section 2.1) may then be applied to calculate the user's position. In the case of advanced systems this course may be plotted on a stored plan of a building or a map of any location, urban or rural.

An example of its operation could involve a user marking their position on entry to a building and then using the track mode to plot their movement and provide markers on the plan of the building, within the navigational aid. The stored information may then be used to guide the person to the exit, or any other chosen destination known to the database. Additional navigation and guidance capability would be possible if the integrated system had a stored map of the interior of the building. This would not only enable the user to be guided to particular locations, but also allow regular correction of navigation errors from way marking as discussed in Chapter 13.

15.7.2 Safety and arming units

A safety and arming unit is a device that ensures a missile has been launched successfully and is clear of its launch point before the warhead is armed ready for activation of its detonation train by its fuze. Clearly, the fundamental requirement is for the launch point to be outside of its warhead’s lethal radius before the arming of the system is implemented. It is conventional for the safety and arming unit to have received positive responses from two independent channels before it activates 'the switch' to arm the warhead.

Accelerometers are commonly used as motion sensors for this type of application. Very simple sensors are adequate to measure motion along the longitudinal axis of the missile, especially for those weapons launched from a trainable launcher. In this case the sensor can be a simple displacement device, where the seismic mass is displaced axially when the longitudinal acceleration exceeds a given value, normally close to the peak acceleration expected from a nominal launch of the missile as it is boosted from a launch rail. The displacement of the seismic mass provides the actuation of one channel of the safety circuit, so closing a switch. An independent technique, such as elapsed time, may be used for the second channel.

The safety and arming unit for a vertically-launched missile is potentially more complex, as it is crucial to ensure that the weapon has made the appropriate manoeuvre before arming its warhead. In this case the inertial measurement unit can provide the requisite data to indicate a successful turnover manoeuvre has been completed. These data can then be used to identify the position when the missile has moved beyond the safety zone around the launch canister by applying simple navigation algorithms. In this case relatively low accuracy sensors are required. The logic of the double switch system is shown in Figure 15.33.

In the case of command-guided missiles the arming function can be activated once the missile has been 'gathered' by the ground-based tracking system and is being guided towards its target. The ground-based tracker and the longitudinal acceleration measurement may be used to provide the independent channels for arming the lethal
Figure 15.33 Safety and arming unit logic

payload. Figure 15.34 shows the position of a compact safety and arming unit within a nose cone of a shell, where it is an integral part of the system’s fuze.

15.7.3 Aircraft ejection seats

The use of ejection seats in fast jet aircraft, and many other military combat aircraft, has saved the lives of many thousands of aircrew since the invention of this safety system more than 50 years ago. As the combat aircraft have become more sophisticated the demands on the ejection seat technology have also increased dramatically, particularly if the ejection process occurs close to the ground and the stricken aircraft is out of control, so that it may be rolling rapidly. Clearly, the use of a simple ballistic ejection technique is not adequate in these circumstances if the crew are going to have a high probability of surviving the ejection from the aircraft.

In the case of any form of rolling motion of the airframe, it is crucially important that the ejection of the seat and its occupant does not occur when the aircraft is inverted and close to the ground. In this case the aircraft’s IN system can organise the ejection process so that the aircrew and their seats are directed into the upper hemisphere away from the ground, as the IN system will know ‘which direction is up’.

The use of an inertial measurement unit on each ejection seat offers the opportunity to control the direction of the ejection if the ejection motor or the seat assembly has some form of control system to manoeuvre the seat and its occupant. A favoured technique would involve thrust vector control of the ejection-seat motor. This approach could manage the direction of the ejection-motor thrusts, and consequently the direction of the trajectory of the seat, to ensure the aircrew has an optimum chance of survival. This type of control system also offers the opportunity to manage the ejection process and minimise the impact of the ejection-induced shocks on the occupant
Figure 15.34 Safety and arming unit in a shell

as well as determining when it is best for the occupant to separate from their seat and descend back to Earth on their parachute.

A simple IMU may also be used to direct the trajectory, as well as controlling the thrust dynamics, of each of the ejection seats during a multiple-seat ejection. This would reduce the probability of the seats colliding or interfering with each other during the ejection process from the aircraft.

The requirements on the inertial sensors are not particularly stringent in terms of the performance accuracy; the devices are only required to operate over a relatively short period, consequently low-performance devices will be adequate. The most demanding requirement is for the sensors to withstand the shocks imparted to the seat system during the ejection process.
15.7.4 Agricultural survey

The use of precision navigation techniques has been applied to the farming [27–29] industry in order to optimise the utilisation of the land. A number of institutions are devising techniques based on precision inertial navigation methods, with differential GPS (described in Section 13.3.2), to use the great positional accuracy for guiding the machinery for ploughing and other functions, from planting to harvesting.

Many combine harvesters throughout the world carry a range of sophisticated equipment to analyse the yield of a crop as it is gathered. An inertial navigation system, with GPS aiding and a reference, may provide a data stream with the co-ordinates of the vehicle, so that the yield can be correlated with an area of the field. Processing of the yield and the associated positional data can enable optimised performance to be achieved in the future, for example, by providing information on where additional fertiliser is required, or where an alternative crop may be successful.

A further example is the automatic control of the tractor during the sowing of seeds in very large fields to enable accurate and efficient planting without missing zones or 'double' planting. This may be considered a form of advanced cruise control for tractors.

15.7.5 Artillery pointing

An enduring requirement of military forces is to know precisely where they are within the battle space, that is, having the ability to establish a precise geographic reference for each system rapidly. This is particularly true for those units involved in the indirect battle, for example artillery batteries using systems with unguided projectiles.

Up to the 1970s, the deployment of artillery required many hours (or possibly days) of work with theodolites to survey the position of the intended gun battery system, prior to occupation. Once the survey had been completed and the battery centre determined, the guns were then aimed along an azimuth determined by magnetic-heading measurement, or, if cost and time permitted, by alignment/orientation transfer from a gyroscopic theodolite.

By the late 1970s an automated survey system known as 'PADS' (position and azimuth determining inertial systems) was developed in the United States and the United Kingdom, which replaced the increasingly outdated method of theodolite survey. PADS allowed a mobile artillery battery to set up, aim, fire its guns in a relatively short period, of the order of 90 min. The introduction of PADS heralded the dawn of mobile artillery operations and gave batteries the unprecedented ability to manoeuvre, set up and fire one accurate salvo, and depart before the enemy could retaliate, a philosophy known as 'shoot and scoot'.

PADS works using a conventional inertial navigation system, and incorporates an inertial grade floated rate-integrating gyroscope with bias of about 0.005°/h. The system is aided by use of a ‘zero-velocity-updating’ algorithm, which allows it to measure and model its error states when it is known to be stationary. With a low-noise
gimballed system, errors in positional estimates can thus be reduced to centimetres, and heading orientation can be estimated to fractions of a milliradian. However, a PADS is both heavy and expensive, and generally could only be deployed on a one-per-battery basis, although in a few cases, armies have used them on a one-per-gun basis. A picture of PADS is shown in Figure 15.35.

The development and widespread availability of inexpensive and accurate satellite-based navigation systems has now generally superseded the use of PADS for survey. Indeed GPS and similar technology is sufficiently cheap to enable the fitting of GPS receivers to individual guns. However, there are, as yet, no effective replacements for the use of inertial techniques for rapidly determining azimuthal orientation accurately.

Nowadays, a strapdown system, aided by odometer and/or GPS, with zero-velocity updating, can provide the required azimuth accuracy with a cost and weight of about a quarter of that of earlier-generation PADS. Moreover, the modern system may also be sufficiently light and rugged to be mounted directly on the trunnion, giving accurate elevation measurement as well. A typical example is the BAE Systems FIN 3110 system used on the British Army’s new Light Gun, and in several other similar applications. A picture of a gun system is shown in Figure 15.36.

A few other complications associated or encountered with the typical implementation of these systems need to be compensated for. First, the problem of ‘track slip’ in tracked vehicles where an odometer is used as an aiding source during the navigation phase. Second, the problem of the shock (up to several hundred g’s) transmitted at the instant of firing – well beyond the linear range of inertial-grade accelerometers. Algorithms to overcome these problems of track slip are now mature and robust.
15.7.6 Other unusual applications

The use of inertial sensors and navigation techniques continues to grow rapidly, particularly with the reduction in cost of the sensors and the wide availability of satellite navigation systems. These developments have encouraged the application of these techniques to conservation, recreation, resource management search and rescue and transport. Some examples of these established and proposed applications are considered below:

- survey of forests to locate specific species;
- monitoring of oil slicks and spills;
- survey of remote areas for location of specific features, such as those suitable for archaeological investigation;
- tracking animals during migration or at other times, for example, during release from captivity;
- an aid for hikers in unfamiliar territory;
- an aid for golfers to determine the distance to the next hole;
- provide the proof that a glider pilot has followed a particular course and reached the turning points;
- marking points for further investigation, such as treasure hunting;
- automatic collection of tolls from vehicles fitted with the appropriate systems;
- position marking in remote areas for dispatch of emergency services;
- monitoring the position and operational use of road vehicles in a fleet;
- precision positioning of equipment, such as excavation or drilling equipment in remote or featureless terrain, including on the seabed;
- tunnelling aids for projects under the sea or through mountains;
• stabilisation of hand-held optical devices and equipment, such as video cameras, binoculars and telescopes.

15.8 Concluding remarks

The range of applications which make use of inertial sensor technology is extremely broad, and is expanding rapidly, as illustrated by the examples given in this chapter. In designing systems for these varied roles, it is essential to consider the full context of the application, taking careful account of issues such as dynamic measurement range and the full range of environmental factors that may have a major impact on the design.

In many of these new or novel applications the catalyst for their development has been the availability of low-cost miniature inertial sensors that offer high reliability and require little or no maintenance. In general, these devices are rugged so that they can be used in relatively hostile environments although, quite often, the measurement accuracy is mediocre. However, the quality of the sensor performance has proved to be well matched to the fundamental requirement, that is, only an indication of angular rate was required to fulfil the task.

The development of integrated navigation techniques, particularly with IN sensors and satellite-based navigation systems, has led to devices that provide accurate navigational aids at a low price. This approach has seen the integrated navigation systems and devices displace high-performance IN systems from some traditional applications, a trend that is likely to continue.

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