CHAPTER

Navigational Sensors

17

CHAPTER CONTENTS

In this chapter, the separation of "vehicle navigational sensors" from "survey navigational sensors" will be examined along with their configurations and applications. Each of the typical survey-grade sensor's principles of operation is examined with the goal of creating a basic reader understanding of each sensor's function (vis-à-vis the task being performed). There are a wide range of sensor variations (technology, accuracy, etc.) regarding the sensors explained below; therefore, each sensor must be analyzed so as to gain a full understanding of its function and utilization.

17.1 Payload sensors versus vehicle sensors

As explained in Chapter 11, typical commercial ROV systems come equipped with a basic set of sensors for navigating the vehicle under normal conditions. These sensors are typically of a lower sensitivity as the need to position a vehicle in a basic orientation of heading/depth is simple.

For tasks demanding a higher tolerance of location (such as for most survey tasks), a much tighter tolerance for positional error is demanded. This is especially true for such tasks as pipeline survey, drilling rig/drill bit placement, or some subsea construction operations. As a result, the end-customer will require the surveyors to assure accurate and reliable vehicle positioning/orientation. Table 17.1 provides some examples of vehicle sensors versus survey sensors.

Further, the survey-grade sensor will typically have a much higher accuracy than a similar vehicle sensor. Communication with the vehicle sensors is normally performed through the vehicle's telemetry system. The survey sensor, however, is typically broken out of the vehicle's telemetry system and is isolated into a completely separate communications channel (most times with its own 1 atm pressure housing), known as a survey "pod" or "mux", which is conducted through a separate fiber (or copper) conductor in the tether. Normally, the only commonality between the vehicle's sensors and the survey "pod/mux" is common power from the vehicle's power bus.

17.1.1 Division of responsibility between ROV and survey functions

On most commercial operations, the survey function is separated from the ROV function as the two skills are unique. The survey function is responsible for accurate placement and depiction of sensor placement (i.e., geo-location) as well as the correlating of sensor readings to geo-referenced coordinates. The ROV function is simply to assure the vehicle is operational and directed to the location of the client's choosing. The survey crew typically collects and processes the data into a final deliverable.

Standard practice in the offshore oil and gas industry (as well as most other commercial applications) is for the survey team to be responsible for all items of survey and positioning above what is provided by the ROV as standard equipment. Examples of survey equipment responsibility are vehicle-mounted acoustic transponders (and conductivity, temperature, and depth (CTD) sensors for sound velocity calibration), 3D multibeam sonar, altimeter, survey-grade gyro, and other mission-specific navigational sensors.

Table 17.1 Examples of Vehicle Versus Survey Sensors

Vehicle Sensors	Survey Sensors
Flux gate magnetic compass	CTD (for Sound Velocity Profiling)
Pressure-sensitive depth gauge	RLG or FOG for orientation
Tether turn counter	DVL for speed over ground
Vehicle altimeter	Survey altimeter
Vehicle telemetry/diagnostics	Acoustic positioning system

17.1.2 Typical survey "pod/mux" configuration

The survey pod is a power and data connection point linked into a central node for powering sensors (with vehicle power) as well as for data transmission to the surface, typically through the vehicle's tether (Figure 17.1). The pod is the central gathering point where sensor communications are fed into a multiplexer for transmission to the surface. Such transmissions are performed through the tether's dedicated communications channel (typically, a separate and dedicated copper or fiber conductor) to the surface for demultiplexing and then dissemination.

The pod is powered from the junction box through the vehicle's power bus. Depending upon the power requirement of the individual sensor, the sensor may be powered through the pod or directly from the vehicle's power bus. The advantage of a survey pod is easy connection of multiple external sensors (power and data) into the vehicle power and telemetry bus without opening the vehicle's electronics can (with the possibility of electronics damage or mis-wiring).

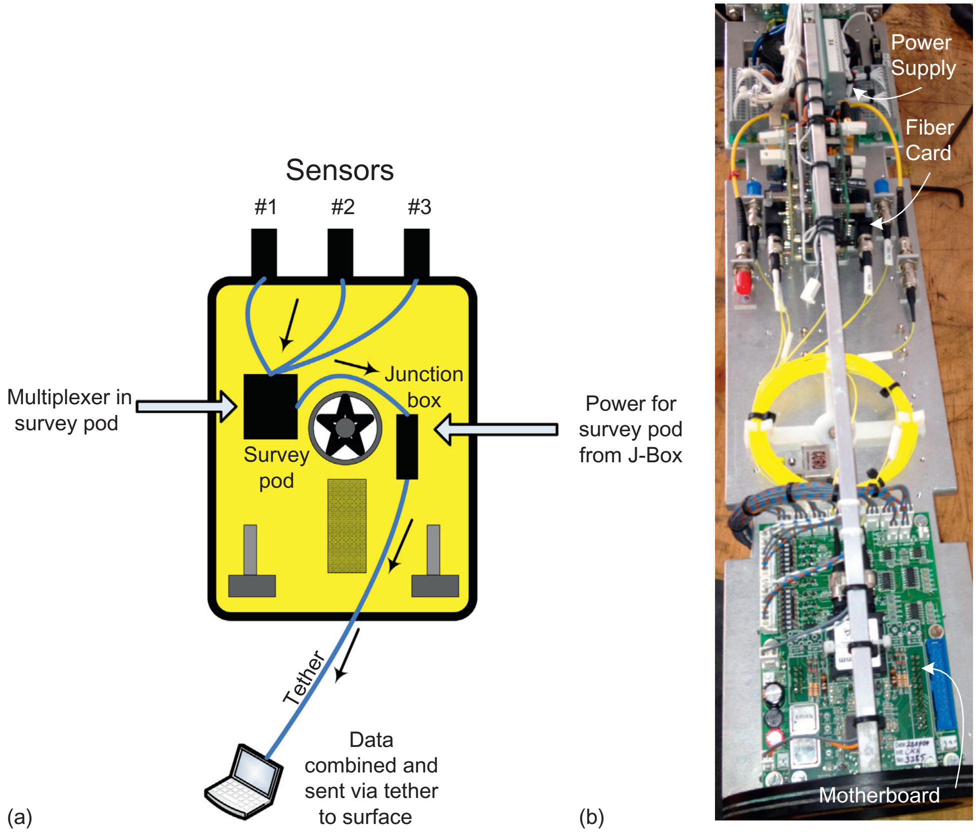

FIGURE 17.1

(a) Typical survey pod integration to vehicle, such as (b) the MacArtney Nexus IV subsea multiplexer.

17.2 Gyros

The gyroscope (referred to as simply a "gyro") is, in its simplest form, a sensor that measures rotation. If one rotates a gyro around its sensitive axis, the gyro will output a signal proportional to the rotation applied. Depending on the technology being employed, this signal can either be in the form of a force (mechanical gyros) or in the form of an electrical signal (optical gyros). An important concept with regard to gyro physics is that a gyro measures rotation in inertial space (i.e., independent of geo-orientation). This means that a gyro will not only measure any rotation applied, it will also measure the rotation of the Earth around its rotational axis. However, it will also measure the rotation of the Earth moving around the sun. In fact, it will even measure the rotation of the Milky Way! Due to most of these signals being too weak, most gyros today will, in practicality, only measure the Earth's rotation. A gyro that can measure the Earth's rotation can also be used to maintain orientation in space independent of the Earth's orientation as well as gravitational influences.

Gyros are used everywhere from intercontinental ballistic missiles to aircraft, ships, and all the way to smart phones. The principle of operation depends upon the technology. The mechanical gyro is based upon the conservation of angular momentum, whereby the spinning gyro tends to continue its orientation unless acted upon by some external force. The basic gyroscopic principle is easily demonstrated with a child's spinning top that will only stay upright as long as the top is spinning. As soon as the top stops spinning, it will lie down on its side. The spinning top needs angular momentum to stay upright. The principle is also easily understood by trying to balance on a bike when it is at a standstill. It becomes much easier once the wheels are spinning and resisting precession (i.e., falling over).

This technology evolves all the way through to portions of an inertial navigation system or to the super-accurate gyrocompasses used in ships as well as spacecraft (and, of course, in underwater vehicles). In the latest iterations of the gyro, optics has replaced mechanics as the source of precession sensing. The optical gyros have certain advantages compared to the mechanical gyro when it comes to size and repeatability due to the lack of moving parts of the optical system.

17.2.1 Mechanical gyros

The earliest mechanical gyros were invented in the classical cultures of Greece, Rome, India, and China (Figure 17.2). However, the modern mechanical gyro was first demonstrated as a useful navigational instrument during an experiment to measure the Earth's rotation by Frenchman Léon Foucault in the 1850s. Foucault named this mechanism the "gyro." The gyro gained wide acceptance in the aviation and maritime industries in the years leading up to and during World War II for accurately measuring aircraft/vessel orientation in three dimensions.

The basic gyro has no orientation with regard to Earth and only measures its orientation with regard to space itself (Figure 17.3). Further, any mechanical gyroscopic system inherently requires some type of suspension system for support of the spinning disk. The mechanical connections introduce some type/measure of friction that causes the gyro to drift over time in an error known as "precession."

For gyros used in navigation, there are two basic types depending upon their seeking capabilities:

1. The slaved gyro (typically, a gyrocompass slaved to (or "seeking") True North) and
2. The unslaved (or "rate") gyro

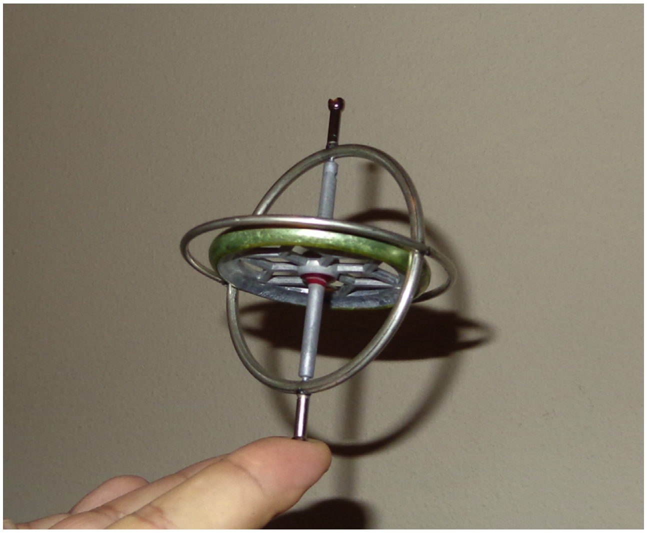

FIGURE 17.2

Mechanical gyro.

(Courtesy Graham Christ.)

17.2.1.1 Slaved gyro

The slaved gyro is arranged to seek some type of reference point (such as True North). Unlike a magnetic compass, whose only orientation is to lines of magnetic flux from the Earth's magnetic field, the gyrocompass senses its precession as it proceeds around the Earth and computes the axis of rotation. As the Earth only rotates in one direction, the pivotal point referencing to True North can then be deduced. For instance, in Figure 17.3, a gyro sitting on a table top located at Point A spins freely about its axis all day without precession as it is colocated on the North Pole (i.e., the pivotal point). A gyro at Point B maintains a constant orientation throughout the day as well since its rotation flows with the Earth's, while Point C has the gyro perpendicular to the table at noon, parallel at 2100, perpendicular again (yet in the opposite orientation) at midnight, and parallel (but flipped from 2100) at 0900. The slaving mechanism measures precession about several axes, thus computing the precession over time to derive True North.

The gyrocompass's (slaved gyro's) function is based upon the following phenomena:

1. *Gyroscopic inertia*: the gyro's conservation of angular momentum (i.e., natural resistance to change in orientation with regard to its inertial frame of reference)
2. *Gyroscopic precession*: the gyro's measured deviation in local frame of reference to the gyro's fixed frame of reference
3. *The Earth's rotation*: the gyro is fixed in space while the gyro's housing (termed the "gyro sphere") is typically fixed to a base (termed the "phantom") upon a floating vessel (which is fixed or floating with reference to Earth)
4. *The Earth's gravity*: for basic orientation to the center of the Earth (for maintaining the gyro's orientation with reference to the horizon—see Figure 17.4)

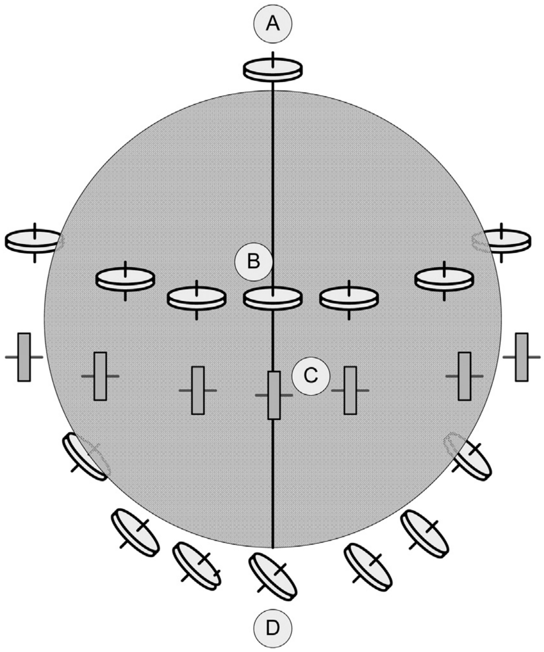

FIGURE 17.3

Gyro maintains orientation irrespective of Earth.

In order for the gyrocompass to seek True North, the gyro must be oriented and maintain the plane of the local meridian (line of longitude) by the gyro's rotor being oriented horizontally (with the help of gravity) as depicted in Figure 17.5. Next, it must remain fixed in this orientation regardless of the motion of the host platform (i.e., the ship or underwater vehicle). As the Earth rotates under the gyro's platform, the plum weight maintaining the gyro sphere's horizontal orientation tends to precess in a direction 90° to the direction of rotation/precession (due to the gyroscopic effect) thus identifying the meridian, and thus True North.

17.2.1.2 Rate gyro

For the simple rate gyro, no slaving is necessary as the only measurement is the rate of precession. Slaved gyros (e.g., gyrocompasses) are used for high-accuracy heading reference (referenced to True North), while rate gyros are used for turn and roll rate or for simple vehicle heading hold (or wing leveling in aircraft) with autopilot functions.

17.2.2 Ring laser gyros

Ring laser gyros (RLG) were developed in the 1960s and are based upon the "Sagnac Effect" (discovered in the early twentieth century by French physicist Georges Sagnac) which states that the timing difference of two light beams traveling in opposite direction around a closed path is directly

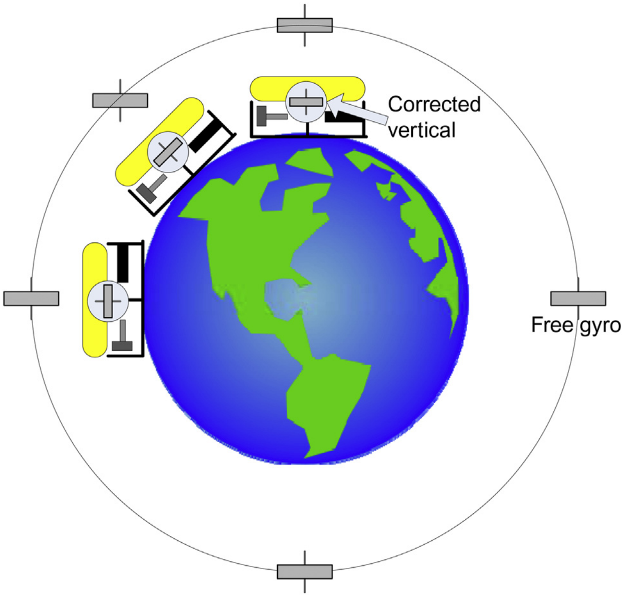

FIGURE 17.4

Free gyro versus gyro maintaining a horizontal plane.

proportional to the rotational speed of the circuit's platform. This phenomenon is the basis for all laser gyro technology.

The reasons a laser is used in RLGs are the laser's unique ability to make use of a single frequency (with small amounts of diffusion), its coherent light beam, and its ability to be focused, split, and deflected. In an RLG, two beams of laser light are projected in opposite directions around a closed circuit (Figure 17.6). The two beams are then joined upon exit of the circuit with the patterns matched in a technique called "interferometry." For a nonrotating gyro, the light patterns match (as both light beams travel the same distance). But when the gyro is rotated, the light patterns then interfere with one another as the light beam traveling in the same direction as the rotation will have traveled a longer distance than the light beam traveling against the rotation. These differences in distance/time cause an interference pattern. The degree of interference is relative to the unit's angular momentum (i.e., rate of turn) that is then measured photometrically. The laser gyros are optimally functional within the plane of the ring (i.e., along the axis of rotation).

The typical RLG has four functional elements:

1. *Excitation mechanism*: A high voltage is applied between a cathode and an anode ionizing a helium–neon gas mixture and producing two beams of light (i.e., lasing) projected in opposite directions.
2. *Gain*: The system's gain helps overcome natural losses by ionizing the low pressure gas mixture producing a fluorescent glow.

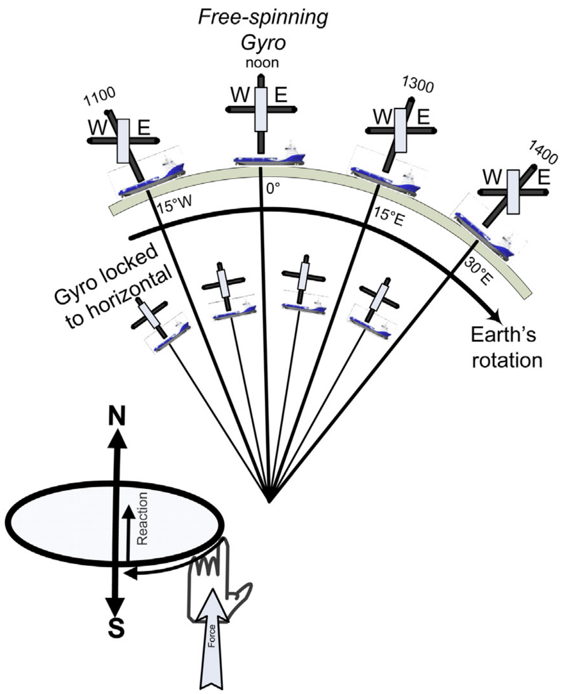

FIGURE 17.5

Depiction of free and horizontally locked gyro as Earth rotates.

3. *Feedback mechanism*: The glowing gas is reflected around corner mirrors (whether the mechanism's shape is square (Figure 17.6) or triangular (Figure 17.7)), allowing the two beams to merge and exit the circuit for pattern matching.
4. *Output coupler*: One of the corners of the unit contains a prism to allow the two beams to mix and form onto the readout detector. Photo diodes measure the light patterns on the fringe of the output, which in turn is converted into electrical pulses for output and measurement. Figure 17.7 depicts a triangular-shaped RLG.

The advantages of the RLG over a mechanical gyro include its long-term stability (mostly due to its solid-state nature with an obvious lack of moving parts), low cost, high reliability, low maintenance, small size/weight, high tolerance to vibration and acceleration, low power requirement, and minimum startup time. Its main disadvantage is its inherent problem of "frequency lock-in" during low-rate turns (i.e., the tendency for the two frequencies to couple together and indicate a zero turning rate although a low-rate turn is in progress).

17.2.3 Fiber-optic gyros

A fiber-optic gyro (FOG) is an RLG with a twist in that the light is directed around many loops of fiber-optic cable (as opposed to a simple enclosed set of mirrors with an RLG). As shown in

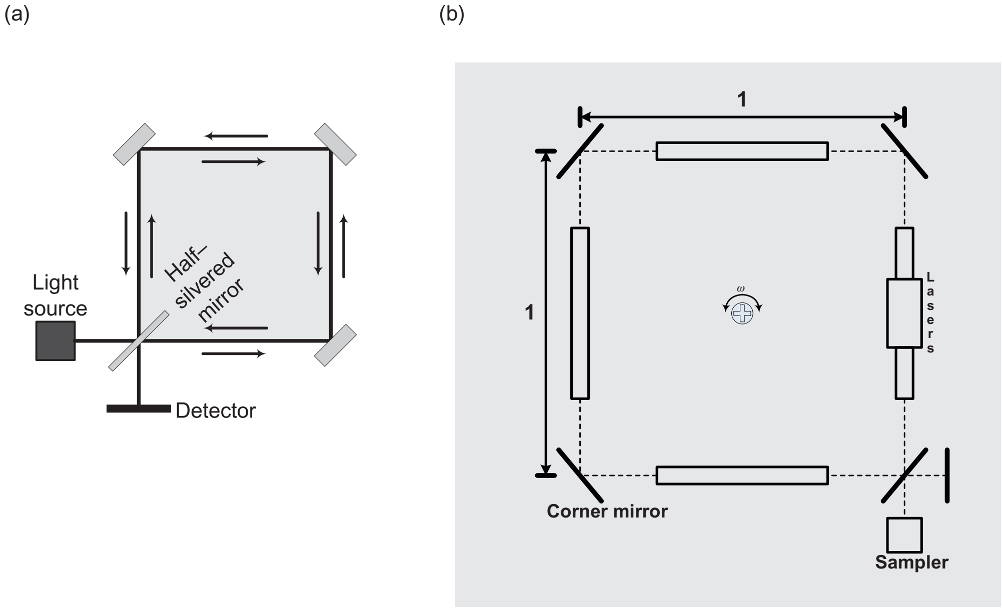

FIGURE 17.6

RLG principle of operation with (a) outside or (b) inline light source.

Figure 17.8, a light source is generated in opposing directions around a coil of fiber. As with the RLG, the beams of light are rejoined and then merged onto a sensor for pattern matching (i.e., rotational measurement). In Figure 17.8, ω is the rotational velocity while $\Delta\varphi$ is the phase difference

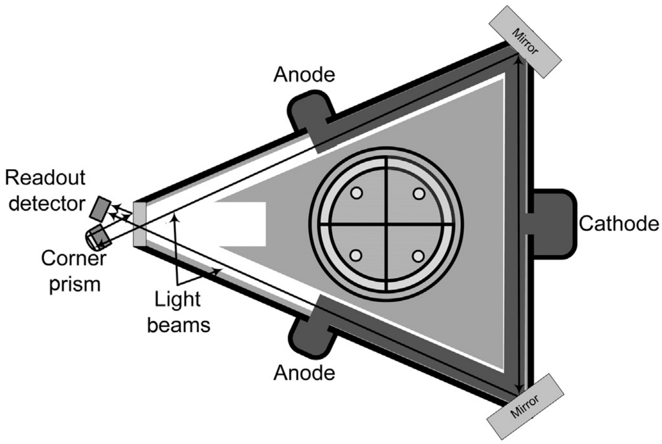

FIGURE 17.7

Triangular RLG.

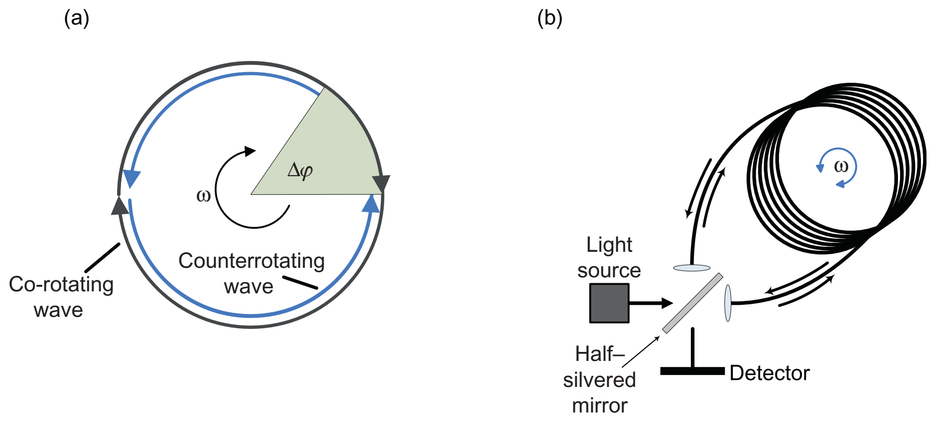

FIGURE 17.8

FOG (a) principle of operation and (b) typical arrangement.

Table 17.2 Advantages and Disadvantages of RLG and FOG

RLG		FOG	
Advantages	**Disadvantages**	**Advantages**	**Disadvantages**
1. No calibration required 2. Highly robust (high MTBF) 3. No moving parts	1. Prone to lockout at low rotational rates	1. Very precise rotational rate 2. Low sensitivity to vibration, acceleration, and shock 3. No moving parts	1. Requires calibration 2. Greater drift than RLG 3. Lower scale factor capability

(measured at the detector) from which ω can be inferred. The advantages and disadvantages of RLG versus FOG are provided in Table 17.2.

The sizes of FOG-based systems do, of course, vary in size depending upon the accuracy needed. As with all gyro systems, accuracy comes with bigger sizes. In order to get an idea of the size, a 0.5° secant latitude Attitude and Heading Reference System (AHRS) system is shown in Figure 17.9.

17.2.4 MEMS-based gyros

The march of technology has accelerated with the advent of MEMS (Micro-Electro-Mechanical-Systems) devices. MEMS is defined as miniaturized mechanical and electromechanical elements (i.e., devices and structure), combined onto a single device, produced by use of microfabrication techniques. This type of device is comprised of microminiaturized sensors, actuators, mechanical components, and electronics integrated into a single chip (which is normally made of silicon).

FIGURE 17.9

The CDL TOGS 2 is a 0.5° secant latitude AHRS system.

(Courtesy CDL.)

This class of sensors has made its way into smart phones, cars, aircraft, spacecraft, and (of course) underwater vehicles. Many MEMS devices have demonstrated performance capabilities exceeding their macroscale counterparts while newer methods of batch fabrication (as used in the integrated circuit industry) translate into a much lower per-device production cost. The main advantages of these types of devices are their ability to be mass-produced, along with their accuracy, low cost, and extremely low size profile and power requirements. However, MEMS gyros can still not compete with high-grade optical or mechanical gyros when it comes to bias stability. For this reason, there is still no True North—seeking MEMS-based system available for civilian use. However, with the current developments within the field, this breakthrough will be achieved within a few years of the writing of this book.

Look for further developments in this area as the technology evolves. This is an exciting area of sensor technology development that has (as the famous Cal Tech scientist Richard Feynman once quipped) "plenty of room at the bottom" (i.e., smaller/faster/cheaper/better).

17.3 Accelerometers

An accelerometer is, in its simplest form, a sensor measuring acceleration. It works on the principle of inertia (Force = Mass × Acceleration) by measuring the force against a known mass in order to derive the unit's acceleration. This means that if a person accelerates an accelerometer on its sensitive axis, the sensor will output a signal proportional to the acceleration applied. As with the gyros, an accelerometer measures acceleration in inertial space. This means that the accelerometer will measure not only any acceleration applied by (for instance) a person moving it around but also the Earth's gravitational acceleration. It will also measure the centripetal acceleration due to the Earth's spinning around its rotational axis.

17.3.1 Pendulum accelerometers

The operation of a pendulum accelerometer is very simple. Imagine holding a string in your hand with a stone attached to the end. If everything is stationary, then the string will hang vertically down from your hand and the angle from your hand to the string will be 90°. If someone then gave you a push on your back, you would move forward and due to the mass of the stone the angle of the string would suddenly not be 90° anymore. The new angle would be proportional to the acceleration applied.

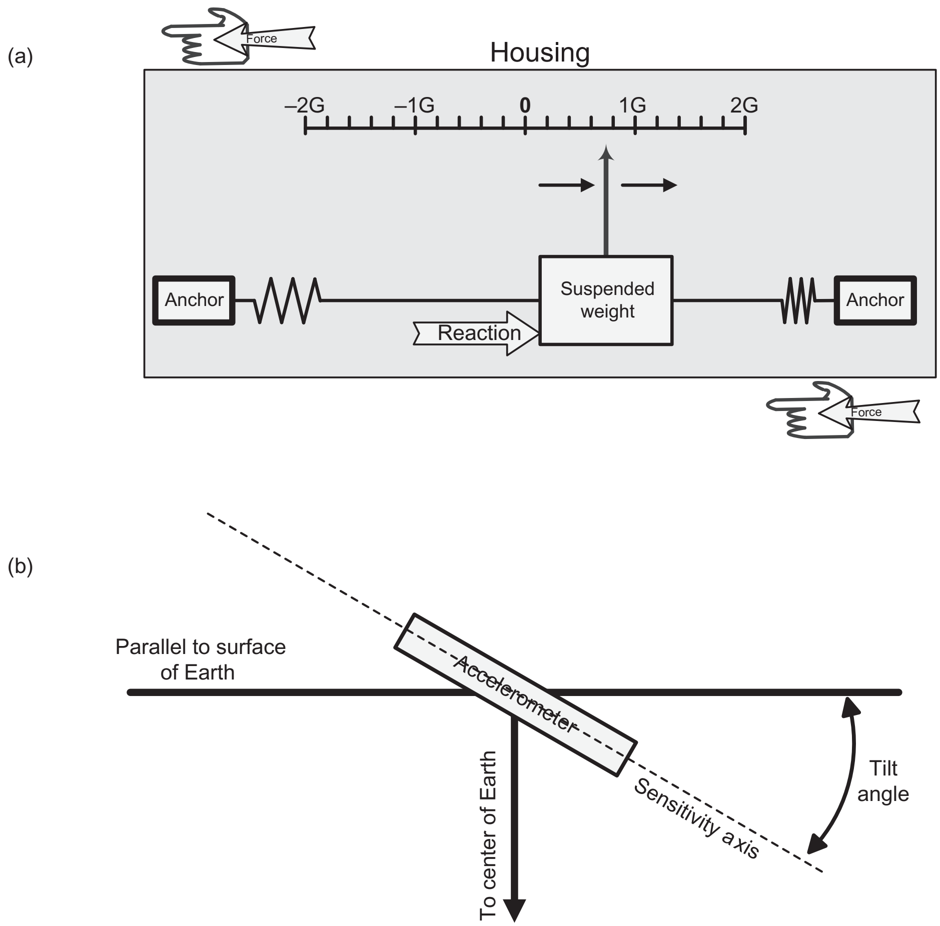

FIGURE 17.10

Accelerometers measure both (a) translational and (b) rotational moments.

In practice, it is (of course) more complicated and normally a pendulum accelerometer would use feedback control to keep the mass close to equilibrium. The amount of feedback needed to keep the mass in equilibrium would then be equivalent to the applied acceleration. Such a system is shown in Figure 17.10.

17.3.2 MEMS-based accelerometers

MEMS-based accelerometers have become very popular over the past 10 years. Due to their size, reliability, and performance, MEMS-based accelerometers are being used in many areas where more "normal" accelerometers were previously the *de facto* standard. As opposed to MEMS-based gyroscopes (which still have not achieved the performance of the high-grade optical/mechanical gyros), the MEMS-based accelerometers have achieved similar performances to the more common technologies. With this high performance, the MEMS-based accelerometers are seen more widely in use due to the obvious advantages in size and price. As with the more ordinary accelerometers, there are many different ways of engineering MEMS-based accelerometers. In order to get an idea of the scale of a MEMS-based magnetic-aided AHRS system, the CDL MiniSense3 is shown in Figure 17.11.

17.4 Inertial navigation systems

Inertial Navigation Systems (INS) are navigational systems capable of calculating position, either relative to some reference system/point or to absolute coordinates. An INS system is composed of

FIGURE 17.11

The CDL MiniSense 3 is a 2° magnetic-aided AHRS system.

(Courtesy CDL.)

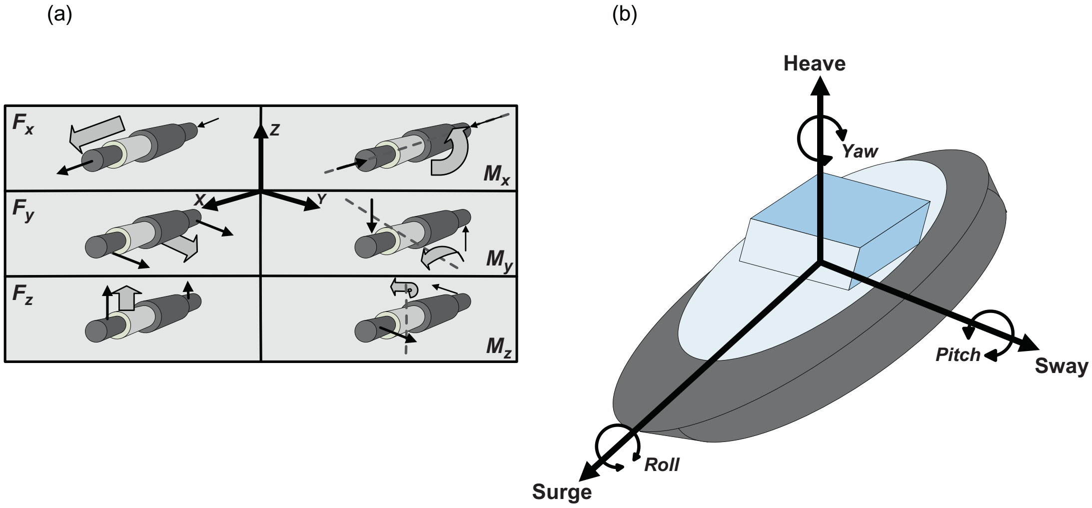

FIGURE 17.12

INS measures movement along the six degrees of freedom displayed as (a) translational (F) along with rotary (M) movement and (b) with vessel superimposed.

at least three gyros and three accelerometers enabling the system to derive a navigation solution. This navigation solution contains at least the position (normally latitude, longitude). Most INS systems today output heading, pitch, and roll. Some systems also include heave, sway, and surge.

The basic concept behind an INS system is the measurement of changes in relative motion (through the measurement of acceleration) to project a changing position in some inertial reference frame over time. The heart of an INS system is its inertial measurement unit (IMU). This mechanism is composed of three orthogonal gyros and three orthogonal accelerometers.

As depicted in Figure 17.12, a full range IMU will measure movement about six degrees of freedom including the three rotational moments M (pitch (M_y), roll (M_x), and yaw (M_z)) and the three translational moments F (heave (F_z), surge (F_x), and sway (F_y)).

The basic concept of an INS system is very simple. Imagine an IMU lying horizontally on a surface placed at the North Pole. The only forces acting on the IMU would then be the Earth's rotation acting on the vertical gyro and the Earth's gravity acting on the vertical accelerometer. If someone then gave the IMU a push forward, the accelerometer having its sensitive axis pointing forward would measure this acceleration. None of the other accelerometers would measure any change. The system would then perform basic deduced reckoning (dead reckoning) to derive an assumed position. A positional error is propagated over time due to the inherent inaccuracies of any inertial sensor. In this simple example, a bias on the accelerometer would cause the position to drift over time. This error (termed "circular error probability," or CEP) is the expected deviation from the computed position derived from the raw measurement. Bowditch (2002) describes CEP as: "*(1) In a circular normal distribution (the magnitudes of the two one-dimensional input errors are equal and the angle of cut is 90°), the radius of the circle containing 50 percent of the individual measurements being made or the radius of the circle inside of which there is a 50 percent probability of being located. (2) The radius of a circle inside of which there* *is a 50 percent probability of being located even though the actual error figure is an ellipse*." That is, the radius of a circle of equivalent probability when the probability is specified as 50%. The CEP measurement is useful in navigation, weapons delivery computations, and search grid designations.

In order to get around this inherent positional drift in INS systems, the survey system is usually augmented by some sort of aiding device. For surface applications, an aiding device could be a global positioning system (GPS). Omega, or Loran. For subsea applications, an aiding device could be USBL, LBL, or DVL. No matter which aiding device is chosen, the purpose is the same: to decrease or even remove inherent drift in INS deduced position.

In order to remove drift in position, a nondrift position-aiding device is needed. This could be a GPS or a USBL system. If a velocity-aiding device like a DVL is used, it will only be possible to decrease the drift in position. The drift is then primarily depending on the DVL velocity accuracy. It is, of course, also possible to aid an INS system with multiple aiding devices, thus gaining redundancy and improved performance.

INS devices are becoming more accurate while being packed in continually smaller units (newer systems are based upon MEMS technology). INS is widely used in subsea vehicle applications as an integral part of the survey package. A size comparison of a FOG-based INS system and a MEMS-based INS system can be seen in Figure 17.13.

FIGURE 17.13

A size comparison between a FOG-based INS system (TOGS 2) (left) and a MEMS-based INS system (MiniSense 3) (right).

(Courtesy CDL.)

17.5 Bathymetric sensors

The science of bathymetry is the study of water depth in lakes and oceans. Early techniques for sampling water depth involved the use of a line with a weight attached. As an interesting side note, in the early days of boating on the Mississippi River the depth was called out in fathoms, often using old-fashioned words for numbers. An expression for a depth of two fathoms would be called out as "mark twain." Samuel Clemens, a former river pilot, took this expression and created his pen name: Mark Twain. This method, while certainly simple and reliable, gave only limited samples in shallow waters. In the early twentieth century, acoustics replaced the weighted line with the single beam sonar, termed a "fathometer" for this application, for measuring depth in fathoms.

Modern bathymetry systems (Figure 17.14) make use of wide-angle hull-mounted or vehicle-mounted multibeam sonar systems, arranged in a fan-like "swath" for mapping large areas of the ocean floor.

17.6 Conductivity, temperature, depth (CTD) sensors

Sound propagates through water at various speeds depending upon the density of the medium. Many factors affect the density of water (which, hence, affects the velocity of sound in water). The three main factors are:

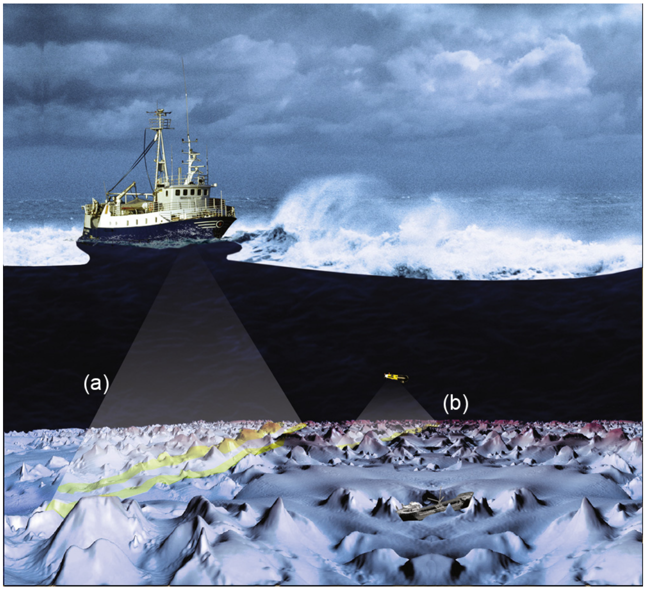

FIGURE 17.14

Depiction of (a) hull-mounted and (b) subsea vehicle-mounted swath bathymetry systems.

(Courtesy Kongsberg Maritime.)

1. Salinity of the water (directly affecting the specific gravity of the water)
2. Temperature (also affecting density)
3. Water depth

As discussed in Chapter 2, water tends to form layers in seawater as depth changes. These layers vary depending upon local heating as well as regional and local water salinity. Cold water is typically denser (up to the 4°C cross-over point for fresh water where ice begins to form) as is higher salinity water. The higher the density of the water, of course, the higher the sound propagation speed.

As depicted in Figure 17.15, if the sound velocity profile (SVP) is not known with some degree of accuracy, large errors in distance (through measurement of inaccurate propagation rate versus time) will occur, thus foiling precise positioning. In order to have accurately derived acoustic positioning, an SVP must be plotted through the water column. The measurement of SVP is the domain of the conductivity/temperature/depth (CTD) sensor.

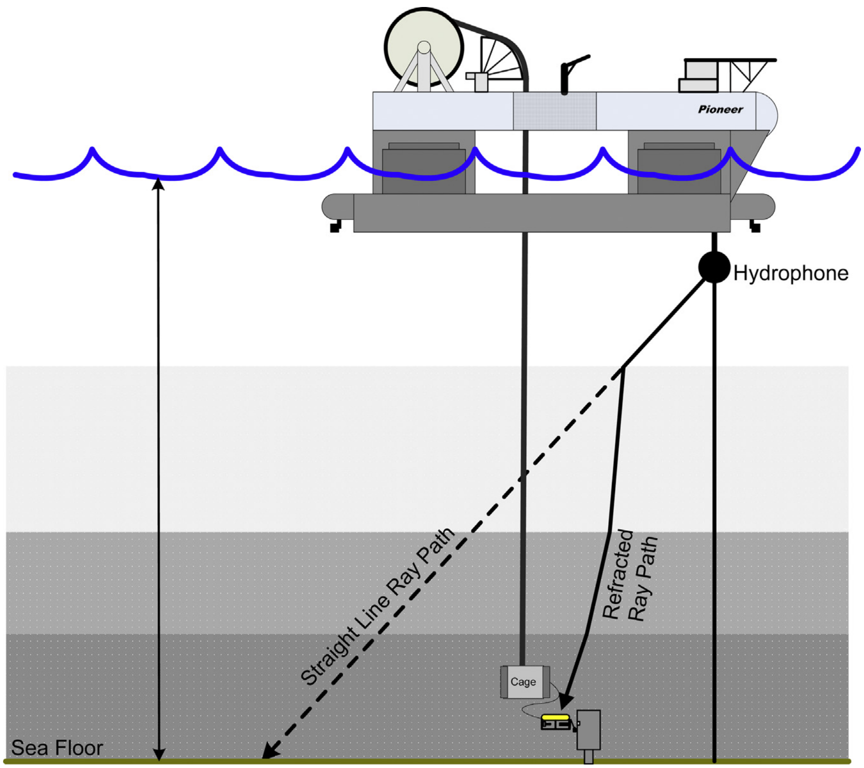

FIGURE 17.15

Differences in CTD distort SVPs.

Conductivity: Fresh water is an insulator, whereas the ever increasing level of salinity in seawater changes the water into a semiconductive medium. Through measuring the level of conductivity of the local water sample, a highly accurate measure of salinity can be derived. The traditional unit of measure for salinity has been parts per thousand (ppt) while the modern measurement unit (since salinity is typically measured electronically) is practical salinity units (PSU).

Temperature: Local water temperature is measured by a device such as a thermistor or some other temperature measurement technology.

Depth: A pressure sensor (of various technologies) is used to measure local water pressure. This measurement is then converted into an accurate measurement of depth, which is then correlated with the conductivity and temperature parameters to derive a full SVP of the water column.

Figure 17.16 and Table 17.3 provide an example of a typical CTD sensor and its operating specifications.

FIGURE 17.16

Citadel CTD-NV CTD sensor.

(Courtesy Teledyne RDI.)

Table 17.3 Operating Specifications for the Citadel CTD-NV

Parameter	Conductivity	Temperature	Depth (Pressure)
Sensor	Inductive cell	Thermistor	Precision-machined silicon
Range	0–9.0 S/m (0–90 mS/cm)	− 5°C to 35°C	Customer specified
Accuracy	± 0.0009 S/m (± 0.009 mS/cm)	± 0.005°C	0.05% full scale
Stability	± 0.01 mS/cm/month	0.0005°C/month	± 0.004%
Resolution	0.00001 S/m (0.0001 mS/cm)	0.001°C	0.001% full scale

17.7 Altimeters

A variation on the hull-mounted depth sounder is the depth sounder mounted to an underwater vehicle decoupled from the surface. While a vessel-mounted depth sounder measures the distance from the hull to the seafloor, the ROV-mounted altimeter measures the distance from the ROV's frame (where the altimeter's transducer attaches) to the seafloor. This, coupled with a pressure-sensitive depth sensor, produces highly accurate local sea bottom profiles.

17.8 Doppler velocity logs

As discussed more fully in Chapter 14, a resolved velocity over bottom can be gained acoustically through use of the Doppler Velocity Log (DVL). Once the over-ground vector is determined, an accurate time/distance calculation can be gained to geo-reference the vehicle's position. In some newer applications, use of a DVL, along with Geographic Information Systems mapping applications, allows for 3D estimated tracking of a submersible with a periodic "snap to grid" updated position through some other technology (e.g., GPS or acoustic positioning). As the vehicle is maneuvered in time/distance navigation mode from a known location, the estimation error, per unit distance or time, is increased proportionally to the distance traveled or time. For instance, if there is an assumed 10% error with the DVL or the INS over distance (or time for that matter) traveled, the error will be 10% for that unit. If another unit of travel distance/time is processed, the error will be that 10% plus another 10% as the circle of possible/probable position increases. The farther the vehicle progresses on dead reckoned navigation without an updated accurate positional fix, the greater the circle of equivalent position probability (also known as CEP).

The principle of operation for a DVL is the same as for the Acoustic Doppler Current Profiler (ADCP), only instead of the upward-looking ADCP (measuring water movement), the DVL looks down (measuring bottom movement). The DVL transmits an array of normally four sonar beams in a generally downward direction toward the bottom, with each beam offset from the vertical in a measured fashion. The echo return frequency is then measured for a Doppler shift—which is proportionate to the speed over ground. In Figure 17.17, the four-transducer array of a DVL is shown along with a graphic of acoustic beam propagation.

DVLs require a bottom to be within a tolerable distance in order to obtain "bottom lock" for the transducers to be able to discern adequate frequency shifts between the beams. Maximum altitudes

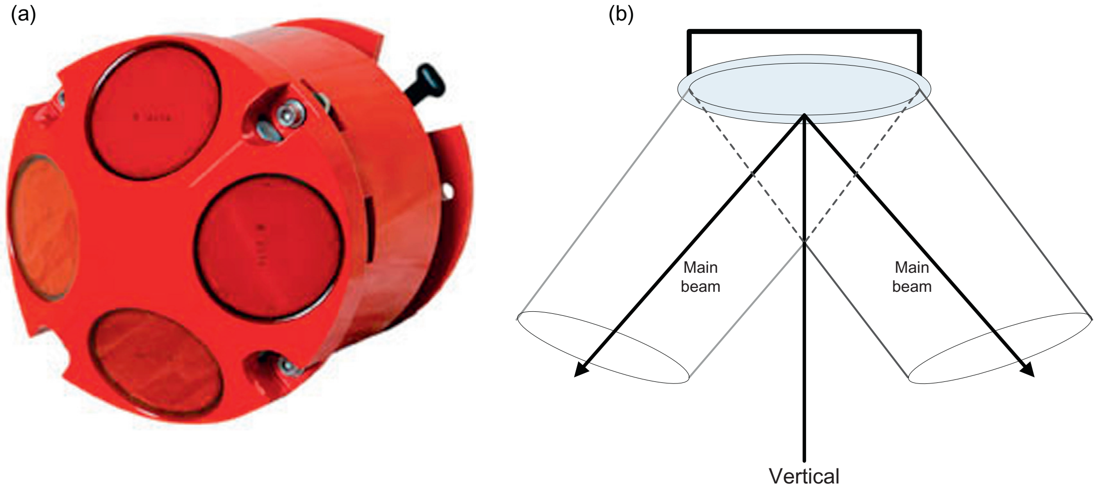

FIGURE 17.17

(a) A Workhorse Navigator DVL along with (b) beam angle illustration (Note: only two of four beams are depicted—the other two are 90° to those shown).

(Courtesy Teledyne RDI.)

are typically 100–650 ft (30–200 m), based upon the frequency used. DVLs are used extensively with subsea vehicle autopilots as well as over-ground navigation systems such as ROV dynamic positioning with relation to the bottom.

17.9 Inclinometers

An inclinometer is a senor for measuring orientation of a vehicle with reference to the gravitational field of the Earth (or other gravitational body). These types of instruments are traditionally used in aircraft and surface ships (even for ground-based measurements) but have found applications in subsea survey.

The inclinometer is critical for orientation of survey sensors within the gravitational frame of reference. The other survey sensors can place the vehicle in a "subsea box" or location, but sensors typically project away from the vehicle. The inclinometer is used to snap the sensor data from a vehicle referenced coordinate frame to an Earth- or gravity-based, referenced frame.

17.10 Long baseline arrays

To summarize the materials mentioned in Chapter 16, as it relates to combined survey instruments, a quick review of acoustic positioning follows. As GPS signals do not travel through water, thus providing the ability to achieve an absolute position fix subsea, some other way of

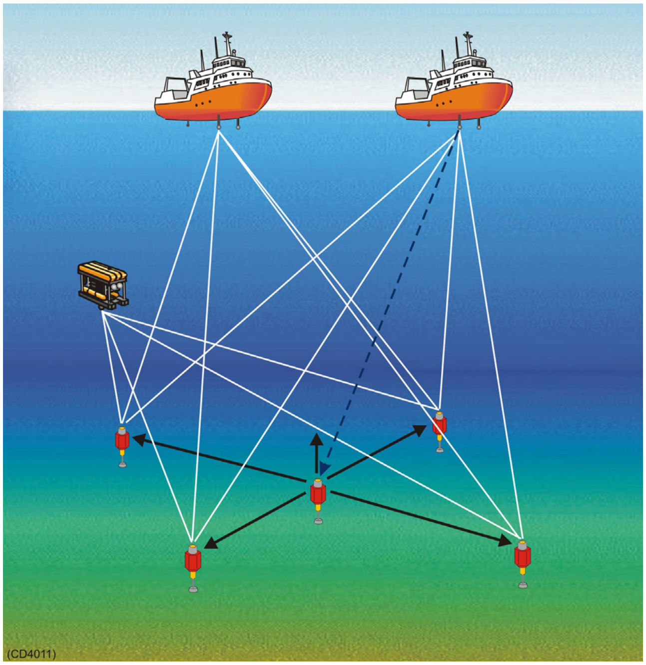

FIGURE 17.18

An LBL array with five surveyed transducers.

(Courtesy Kongsberg Maritime.)

achieving this is required. Using a long baseline (LBL) is a way of achieving a position fix within a confined area.

The basic idea is similar to that of GPS. A number of transducers are surveyed onto the seabed, thus providing an absolute position for each transducer. Any user able to receive the signals from these transducers can then use the time delays and information about each transducer to deduce an absolute position within the LBL network (Figure 17.18).

A well-surveyed high-accuracy LBL array can give positions to within centimeters. The main disadvantage of an LBL array is the cost of surveying (for high-accuracy geo-location) the LBL array. Each transducer needs to be precisely located on the seabed (which is costly). Further, the LBL only works within the area where it is installed and is not easily moved to a new location.

17.11 Ultrashort baseline arrays

An ultrashort baseline (USBL) is a similar technology to LBL. However, the transducers are moved very close together within a single unit. This unit receives a signal from a transponder/responder located on an ROV or a tow body and then calculates the relative position with reference to the ship. If the ship has a known position (e.g., from a GPS), it is easy to deduce the absolute position of the ROV or tow body (or any other client, for that matter).

The way a USBL system calculates the position of a client is to first estimate the distance by simply using the signal's travel time from the client to the USBL array. Knowledge of the speed of sound (rate) through the water column, along with the known propagation time, will give the distance to the client. Analyzing the phase delay across the USBL array will give the angle at which the signal was received. With that information, the position of the client relative to the ship can be derived.

The main disadvantage of the USBL system is the position error. The position error grows proportionally with the slant range. Although USBL systems are improving, a high-grade USBL system would have errors in the area of 0.1% of slant range. This means that if the client is operating at a depth of 10,000 ft (3000 m), the position will only be good to 10 ft (3 m) for zero slant range, with the error scaling as the slant distance increases. Less accurate systems would easily have up to 65–100 ft (20–30 m) of error (without slant range) at a 10,000 ft (3000 m) depth. One of the advantages, as opposed to the LBL array, is that it is very easy to move the USBL from site to site.

17.12 Combined instruments

The trend in subsea vehicle navigation is for manufacturers to combine several sensors into one mechanism, thereby reducing the amount of weight and power draw through sharing pressure

FIGURE 17.19

CDL TOGS-NAV 2 combines several sensors into a single package.

(Courtesy CDL.)

FIGURE 17.20

CDL INStar system combines several sensors and opens up for entirely new applications.

(Courtesy CDL.)

housings and electronic components. Another advantage is that a combined unit can multiplex the different sensors onto one communication line, thus reducing the number of communication lines in the umbilical.

Often an acoustics manufacturer will combine a CTD unit (measuring SVP for corrected positioning measurements) with a sonar or acoustic positioning system, while a gyro manufacturer will combine multiple gyros on differing orientations in order to produce a full accelerometer for use with an inertial navigation system.

The CDL TOGS-NAV 2 (Figure 17.19) is an example of this combination. In this system, an IMU is combined with a DVL, a depth sensor, and a sound velocity probe. This gives a single system capable of outputting heading, pitch, roll, position, velocity, depth, and speed of sound. This has a big advantage compared to having to install and integrate four different systems.

The combining of sensors also reduces installation and integration time. Combining different sensors also extends to creating completely new packages—which opens up new applications that the individual sensors would not be able to achieve as separate stand-alone systems. The CDL INStar is such a system (Figure 17.20). This package combines GPS position with an attitude sensor. It also includes communication via either satellite or radio link. This enables the system to be installed on remote devices or vehicles sending back attitude and position information either via radio link or satellite.