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# *Use of Sensors in Autonomous Systems and their Classification*

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***Abstract***

*One of the most important tasks of an autonomous system of any kind is to acquire knowledge about its environment. This is done by taking measurements using various sensors and then extracting meaningful information from those measurements. In this paper, we present the most common sensors used in mobile robots, classify them, and then discuss strategies for extracting information from the sensors. Sensors can be classified on the basis of two important functional categories: proprioceptive/exteroceptive and passive/active. Proprioceptive sensors are involved in measurement of values that are internal to the system (robot); such as motor speed, wheel load, robot arm joint angles, battery voltage. Exteroceptive sensors get information from a robot's environment; including, sound amplitude, intensity of light, distance measurements, etc*

***Keywords:*** *Sensors in Autonomous Systems, Multi-sensor Systems, Exteroceptive Sensors*

## INTRODUCTION

In this paper, we will focus primarily on sensors used to extract information about a robot's environment. Because a mobile robot moves around, it will frequently encounter unforeseen environmental characteristics, and therefore such sensing is particularly critical. We begin with a functional classification of sensors. Then, after presenting basic tools for describing a sensor's performance, we proceed to describe selected sensors in detail.


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The sensors are classified using two important functional axes: proprioceptive/ exteroceptive and passive/active. Proprioceptive sensors measure values internal to the system (robot); for example, motor speed, wheel load, robot arm joint angles, battery voltage. Exteroceptive sensors acquire information from the robot's environment; for example, distance measurements, light intensity, sound amplitude. Hence exteroceptive sensor measurements are interpreted by the robot in order to extract meaningful environmental features.

**a)**

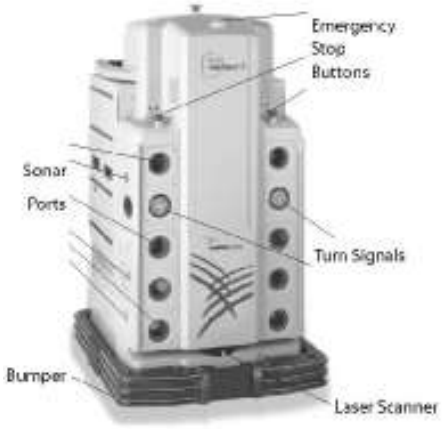



***Figure 1 (a): HelpMate from Transition Research Corporation***

**b)**



***Figure 1 (b): B21 from Real World Interface;***


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***(c)***

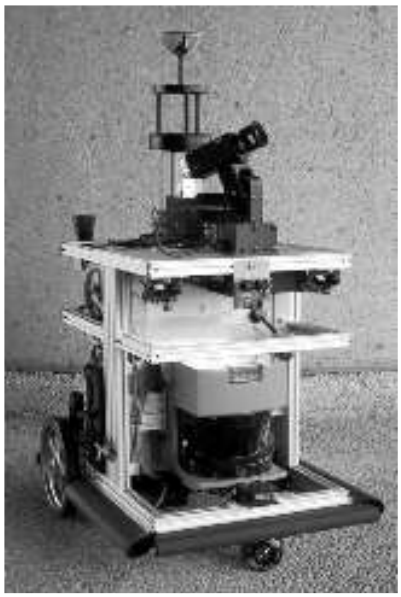


***Figure 1 (c): BIBA Robot, Blue Botics SA***

Passive sensors measure ambient environmental energy entering the sensor. Examples of passive sensors include temperature probes, microphones, and CCD or CMOS cameras. Active sensors emit energy into the environment, then measure the environmental reaction. Because active sensors can manage more controlled interactions with the environment, they often achieve superior performance. However, active sensing introduces several risks: the outbound energy may affect the very characteristics that the sensor is attempting to measure.

Furthermore, an active sensor may suffer from interference between its signal and those beyond its control. For example, signals emitted by other nearby robots, or similar sensors on the same robot, may influence the resulting measurements. Examples of active sensors include wheel quadrature encoders, ultrasonic sensors, and laser rangefinders. Table 1 provides a classification of the most useful sensors for mobile robot applications. The most interesting sensors are discussed in this chapter.


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***Table 1: Classification of sensors used in mobile robotics applications***

| General classification (typical use) | Sensor Sensor System | PC or EC | A or P |
|---|---|---|---|
| Tactile sensors (detection of physical contact or closeness; security switches) | Contact switches, bumpers | EC | P |
| | Optical barriers | EC | A |
| | Noncontact proximity sensors | EC | A |
| Wheel/motor sensors (wheel/motor speed and position) | Brush encoders | PC | P |
| | Potentiometers | PC | P |
| | Synchros, resolvers | PC | A |
| | Optical encoders | PC | A |
| | Magnetic encoders | PC | A |
| | Inductive encoders | PC | A |
| | Capacitive encoders | PC | A |
| Heading sensors (orientation of the robot in relation to a fixed reference frame) | Compass | EC | P |
| | Gyroscopes | PC | P |
| | Inclinometers | EC | A/P |
| Ground-based beacons (localization in a fixed reference frame) | GPS | EC | A |
| | Active optical or RF beacons | EC | A |
| | Active ultrasonic beacons | EC | A |
| | Reflective beacons | EC | A |
| Active ranging (reflectivity, time-of-flight, and geo-metric triangulation) | Reflectivity sensors | EC | A |
| | Ultrasonic sensor | EC | A |
| | Laser rangefinder | EC | A |
| | Optical triangulation (1D) | EC | A |
| | Structured light (2D) | EC | A |
| Motion/speed sensors (speed relative to fixed or moving objects) | Doppler radar | EC | A |
| | Doppler sound | EC | A |
| Vision-based sensors (visual ranging, whole-image analy-sis, segmentation, object recognition) | CCD/CMOS camera(s) | EC | P |
| | Visual ranging packages | | |
| | Object tracking packages | | |

A, active; P, passive; P/A, passive/active; PC, proprioceptive; EC, exteroceptive.

The sensor classes in table 1 are arranged in ascending order of complexity and descending order of technological maturity. Tactile sensors and proprioceptive sensors are critical to virtually all mobile robots, and are well understood and easily implemented. Commercial quadrature encoders, for example, may be purchased as part of a gear-motor assembly used in a mobile robot.

At the other extreme, visual interpretation by means of one or more CCD/CMOS cameras provides a broad array of potential functionalities, from obstacle avoidance and localization to human face recognition. However, commercially available sensor units that provide visual functionalities are only now beginning to emerge [90, 160].


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## CHARACTERIZING SENSOR PERFORMANCE

The sensors we describe in this chapter vary greatly in their performance characteristics. Some sensors provide extreme accuracy in well-controlled laboratory settings, but are overcome with error when subjected to real-world environmental variations. Other sensors provide narrow, high-precision data in a wide variety of settings. In order to quantify such performance characteristics, first we formally define the sensor performance terminology that will be valuable throughout the rest of this paper.

### *Basic Sensor Response Ratings*

A number of sensor characteristics can be rated quantitatively in a laboratory setting. Such performance ratings will necessarily be best-case scenarios when the sensor is placed on a real-world robot, but are nevertheless useful. Dynamic range is used to measure the spread between the lower and upper limits of input values to the sensor while maintaining normal sensor operation. Formally, the dynamic range is the ratio of the maximum input value to the minimum measurable input value. Because this raw ratio can be unwieldy, it is usually measured in decibels, which are computed as ten times the common logarithm of the dynamic range. However, there is potential confusion in the calculation of decibels, which are meant to measure the ratio between powers, such as watts or horsepower. Suppose your sensor measures motor current and can register values from a minimum of 1 mA to 20 Amps. The dynamic range of this current sensor is defined as

$$10 \cdot \log\left[\frac{20}{0.001}\right] = 43 \text{ dB} \quad \textbf{(1)}$$

Now suppose you have a voltage sensor that measures the voltage of your robot's battery, measuring any value from 1 mV to 20 V. Voltage is not a unit of power, but the square of voltage is proportional to power. Therefore, we use 20 instead of 10:

$$20 \cdot \log\left[\frac{20}{0.001}\right] = 86 \text{ dB} \quad \textbf{(2)}$$

Range is also an important rating in mobile robot applications because often robot sensors operate in environments where they are frequently exposed to input values beyond their working range. In such cases, it is critical to understand how the sensor


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will respond. For example, an optical rangefinder will have a minimum operating range and can thus provide spurious data when measurements are taken with the object closer than that minimum. Resolution is the minimum difference between two values that can be detected by a sensor. Usually, the lower limit of the dynamic range of a sensor is equal to its resolution. However, in the case of digital sensors, this is not necessarily so. For example, suppose that you have a sensor that measures voltage, performs an analog-to-digital (A/D) conversion, and outputs the converted value as an 8-bit number linearly corresponding to between 0 and 5 V. If this sensor is truly linear, then it has 28 -1 total output values, or a resolution of 5 V( ) 255 = 20 mV.

Linearity is an important measure governing the behavior of the sensor's output signal as the input signal varies. A linear response indicates that if two inputs x and y result in the two outputs f(x) and f(y), then for any values and a and b, f(ax+by)=af(x) +bf(y). This means that a plot of the sensor's input/output response is simply a straight line.

Bandwidth or frequency is used to measure the speed with which a sensor can provide a stream of readings. Formally, the number of measurements per second is defined as the sensor's frequency in hertz. Because of the dynamics of moving through their environment, mobile robots often are limited in maximum speed by the bandwidth of their obstacle detection sensors. Thus, increasing the bandwidth of ranging and vision-based sensors has been a high-priority goal in the robotics community.

**In situ sensor performance**

The above sensor characteristics can be reasonably measured in a laboratory environment with confident extrapolation to performance in real-world deployment.

However, a number of important measures cannot be reliably acquired without deep understanding of the complex interaction between all environmental characteristics and the sensors in question. This is most relevant to the most sophisticated sensors, including active ranging sensors and visual interpretation sensors. Sensitivity itself is a desirable trait. This is a measure of the degree to which an incremental change in the target input signal changes the output signal. Formally, sensitivity is the ratio of output change to input change.


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Unfortunately, however, the sensitivity of exteroceptive sensors is often confounded by undesirable sensitivity and performance coupling to other environmental parameters.

Cross-sensitivity is the technical term for sensitivity to environmental parameters that are orthogonal to the target parameters for the sensor. For example, a flux-gate compass can demonstrate high sensitivity to magnetic north and is therefore of use for mobile robot navigation. However, the compass will also demonstrate high sensitivity to ferrous building materials, so much so that its cross-sensitivity often makes the sensor useless in some indoor environments. High cross-sensitivity of a sensor is generally undesirable, especially when it cannot be modeled.

Error of a sensor is defined as the difference between the sensor's output measurements and the true values being measured, within some specific operating context. Given a true value v and a measured value m, we can define error as error = m – v.

Accuracy is defined as the degree of conformity between the sensor's measurement and the true value, and is often expressed as a proportion of the true value (e.g., 97.5% accuracy). Thus small error corresponds to high accuracy and

(accuracy= 1|error|/v**)** **(3)**

Of course, obtaining the ground truth, v, can be difficult or impossible, and so establishing a confident characterization of sensor accuracy can be problematic. Further, it is important to distinguish between two different sources of error: Systematic errors are caused by factors or processes that can in theory be modeled. These errors are, therefore, deterministic (i.e., predictable). Poor calibration of a laser rangefinder, an unmodeled slope of a hallway floor, and a bent stereo camera head due to an earlier collision are all possible causes of systematic sensor errors. Random errors cannot be predicted using a sophisticated model nor can they be mitigated by more precise sensor machinery. These errors can only be described in probabilistic terms (i.e., stochastically). Hue instability in a color camera, spurious range finding errors, and black level noise in a camera are all examples of random errors. Precision is often confused with accuracy, and now we have the tools to clearly distinguish these two terms. Intuitively, high precision relates to reproducibility of the sensor results. For


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example, one sensor taking multiple readings of the same environmental state has high precision if it produces the same output. In another example, multiple copies of this sensor taking readings of the same environmental state have high precision if their outputs agree. Precision does not, however, have any bearing on the accuracy of the sensor's output with respect to the true value being measured. Suppose that the random error of a sensor is characterized by some mean value and a standard deviation σ. The formal definition of precision is the ratio of the sensor's output range to the standard deviation**.**

precision = range/σ□□□□□□□□□□□□□□□□□□□□□□□□□□□□□□□□

Note that only σ and μnot has impact on precision. In contrast, mean error is directly proportional to overall sensor error and inversely proportional to sensor accuracy.
Characterizing error: the challenges in mobile robotics

Mobile robots depend heavily on exteroceptive sensors. Many of these sensors concentrate on a central task for the robot: acquiring information on objects in the robot's immediate vicinity so that it may interpret the state of its surroundings. Of course, these "objects" surrounding the robot are all detected from the viewpoint of its local reference frame. Since the systems we study are mobile, their ever-changing position and their motion have a significant impact on overall sensor behavior. In this section, empowered with the terminology of the earlier discussions, we describe how dramatically the sensor error of a mobile robot disagrees with the ideal picture drawn in the previous section.

- Blurring of systematic and random errors. Active ranging sensors tend to have failure modes that are triggered largely by specific relative positions of the sensor and environment targets. For example, a sonar sensor will produce specular reflections, producing grossly inaccurate measurements of range, at specific angles to a smooth sheetrock wall. During motion of the robot, such relative angles occur at stochastic intervals. This is especially true in a mobile robot outfitted with a ring of multiple sonars. The chances of one sonar entering this error mode during robot motion is high. From the


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perspective of the moving robot, the sonar measurement error is a random error in this case. Yet, if the robot were to stop, becoming motionless, then a very different error modality is possible. If the robot's static position causes a particular sonar to fail in this manner, the sonar will fail consistently and will tend to return precisely the same (and incorrect!) reading time after time. Once the robot is motionless, the error appears to be systematic and of high precision.

The fundamental mechanism at work here is the cross-sensitivity of mobile robot sensors to robot pose and robot-environment dynamics. The models for such cross-sensitivity are not, in an underlying sense, truly random. However, these physical interrelationships are rarely modeled and therefore, from the point of view of an incomplete model, the errors appear random during motion and systematic when the robot is at rest.

Sonar is not the only sensor subject to this blurring of systematic and random error modality. Visual interpretation with a CCD camera is also highly susceptible to robot motion and position because of camera dependence on lighting changes, lighting specularity (e.g., glare), and reflections. The important point is to realize that, while systematic error and random error are well-defined in a controlled setting, the mobile robot can exhibit error characteristics that bridge the gap between deterministic and stochastic error mechanisms.

- ***Multimodal error distributions***

It is common to characterize the behavior of a sensor's random error in terms of a probability distribution over various output values. In general, one knows very little about the causes of random error and therefore several simplifying assumptions are commonly used. For example, we can assume that the error is zero-mean, in that it symmetrically generates both positive and negative measurement error. We can go even further and assume that the probability density curve is Gaussian. Although we discuss the mathematics of this in detail in section 4.2, it is important for now to recognize the fact that one frequently assumes symmetry as well as unimodal distribution. This means that measuring the correct value is most probable, and any measurement that is further away from the correct value is less likely than any measurement that is closer to the correct value. These are strong assumptions that


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enable powerful mathematical principles to be applied to mobile robot problems, but it is important to realize how wrong these assumptions usually are. Consider, for example, the sonar sensor once again. When ranging an object that reflects the sound signal well, the sonar will exhibit high accuracy, and will induce random error based on noise, for example, in the timing circuitry. This portion of its sensor behavior will exhibit error characteristics that are fairly symmetric and unimodal. However, when the sonar sensor is moving through an environment and is sometimes faced with materials that cause coherent reflection rather than returning the sound signal to the sonar sensor, then the sonar will grossly overestimate the distance to the object. In such cases, the error will be biased toward positive measurement error and will be far from the correct value. The error is not strictly systematic, and so we are left modeling it as a probability distribution of random error. So the sonar sensor has two separate types of operational modes, one in which the signal does return and some random error is possible, and the second in which the signal returns after a multipath reflection, and gross overestimation error occurs. The probability distribution could easily be at least bimodal in this case, and since overestimation is more common than underestimation it will also be asymmetric. As a second example, consider ranging via stereo vision. Once again, we can identify two modes of operation. If the stereo vision system correctly correlates two images, then the resulting random error will be caused by camera noise and will limit the measurement accuracy. But the stereo vision system can also correlate two images incorrectly, matching two fence posts, for example, that are not the same post in the real world. In such a case stereo vision will exhibit gross measurement error, and one can easily imagine such behavior violating both the unimodal and the symmetric assumptions. The thesis of this section is that sensors in a mobile robot may be subject to multiple modes of operation and, when the sensor error is characterized, unimodality and symmetry may be grossly violated. Nonetheless, as we shall see, many successful mobile robot systems make use of these simplifying assumptions and the resulting mathematical techniques with great empirical success.

The above sections have presented a terminology with which we can characterize the advantages and disadvantages of various mobile robot sensors. In the following


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sections, we do the same for a sampling of the most commonly used mobile robot sensors today.

## WHEEL/MOTOR SENSORS

Wheel/motor sensors are devices used to measure the internal state and dynamics of a mobile robot. These sensors have vast applications outside of mobile robotics and, as a result, mobile robotics has enjoyed the benefits of high-quality, low-cost wheel and motor sensors that offer excellent resolution. In the next section, we sample just one such sensor, the optical incremental encoder.

### *Optical Encoders*

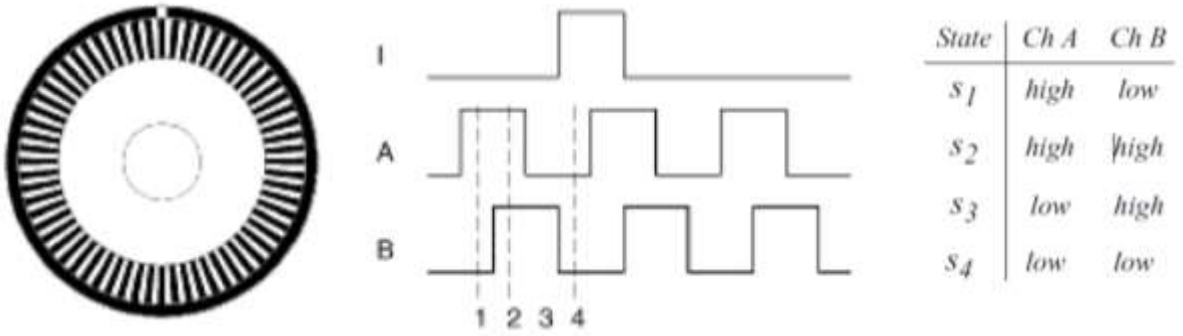
Optical incremental encoders have become the most popular device for measuring angular speed and position within a motor drive or at the shaft of a wheel or steering mechanism. In mobile robotics, encoders are used to control the position or speed of wheels and other motor-driven joints. Because these sensors are proprioceptive, their estimate of position is best in the reference frame of the robot and, when applied to the problem of robot localization, significant corrections are required.

An optical encoder is basically a mechanical light chopper that produces a certain number of sine or square wave pulses for each shaft revolution. It consists of an illumination source, a fixed grating that masks the light, a rotor disc with a fine optical grid that rotates with the shaft, and fixed optical detectors. As the rotor moves, the amount of light striking the optical detectors varies based on the alignment of the fixed and moving gratings. In robotics, the resulting sine wave is transformed into a discrete square wave using a threshold to choose between light and dark states. Resolution is measured in cycles per revolution (CPR). The minimum angular resolution can be readily computed from an encoder's CPR rating. A typical encoder in mobile robotics may have 2000 CPR, while the optical encoder industry can readily manufacture encoders with 10000 CPR. In terms of required bandwidth, it is of course critical that the encoder be sufficiently fast to count at the shaft spin speeds that are expected. Industrial optical encoders present no bandwidth limitation to mobile robot applications.

Usually in mobile robotics the quadrature encoder is used. In this case, a second illumination and detector pair is placed 90


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degrees shifted with respect to the original in terms of the rotor disc. The resulting twin square waves, shown in figure 2, provide significantly more information. The ordering of which square wave produces a rising edge first identifies the direction of rotation. Furthermore, the four detectably different states improve the resolution by a factor of four with no change to the rotor disc. Thus, a 2000 CPR encoder in quadrature yields 8000 counts. Further improvement is possible by retaining the sinusoidal wave measured by the optical detectors and performing sophisticated interpolation. Such methods, although rare in mobile robotics, can yield 1000-fold improvements in resolution. As with most proprioceptive sensors, encoders are generally in the controlled environment of a mobile robot's internal structure, and so systematic error and cross-sensitivity can be engineered away. The accuracy of optical encoders is often assumed to be 100% and, although this may not be entirely correct, any errors at the level of an optical encoder are dwarfed by errors downstream of the motor shaft.




| State | Ch A | Ch B |
|---|---|---|
| $s_1$ | high | low |
| $s_2$ | high | high |
| $s_3$ | low | high |
| $s_4$ | low | low |

***Figure 2 Quadrature optical wheel encoder: The observed phase relationship between channel A and B pulse trains are used to determine the direction of the rotation. A single slot in the outer track generates a reference (index) pulse per revolution.***

**HEADING SENSORS**

Heading sensors can be proprioceptive (gyroscope, inclinometer) or exteroceptive (compass). They are used to determine the robot's orientation and inclination. They allow us, together with appropriate velocity


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information, to integrate the movement to a position estimate. This procedure, which has its roots in vessel and ship navigation, is called dead reckoning.

***Compasses***

The two most common modern sensors for measuring the direction of a magnetic field are the Hall effect and flux gate compasses. Each has advantages and disadvantages, as described below.

The Hall effect describes the behavior of electric potential in a semiconductor when in the presence of a magnetic field. When a constant current is applied across the length of a semiconductor, there will be a voltage difference in the perpendicular direction, across the semiconductor's width, based on the relative orientation of the semiconductor to magnetic flux lines. In addition, the sign of the voltage potential identifies the direction of the magnetic field. Thus, a single semiconductor provides a measurement of flux and direction along one dimension. Hall effect digital compasses are popular in mobile robotics, and contain two such semiconductors at right angles, providing two axes of magnetic field (thresholded) direction, thereby yielding one of eight possible compass directions. The instruments are inexpensive but also suffer from a range of disadvantages. Resolution of a digital Hall effect compass is poor. Internal sources of error include the nonlinearity of the basic sensor and systematic bias errors at the semiconductor level. The resulting circuitry must perform significant filtering, and this lowers the bandwidth of Hall effect compasses to values that are slow in mobile robot terms. For example, the Hall effect compass pictured in figure 3 needs 2.5 seconds to settle after a 90 degree spin.

The flux gate compass operates on a different principle. Two small coils are wound on ferrite cores and are fixed perpendicular to one another. When alternating current is activated in both coils, the magnetic field causes shifts in the phase depending on its relative alignment with each coil. By measuring both phase shifts, the direction of the magnetic field in two dimensions can be computed.


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***Figure 3 Digital compass: Sensors such as the digital/analog Hall effect sensor shown, available from Dinsmore (http://dinsmoregroup.com/dico), enable inexpensive (< $ 15) sensing of magnetic fields.***

The flux gate compass can accurately measure the strength of a magnetic field and has improved resolution and accuracy; however, it is both larger and more expensive than a Hall effect compass. Regardless of the type of compass used, a major drawback concerning the use of the Earth's magnetic field for mobile robot applications involves disturbance of that magnetic field by other magnetic objects and man-made structures, as well as the bandwidth limitations of electronic compasses and their susceptibility to vibration. Particularly in indoor environments, mobile robotics applications have often avoided the use of compasses, although a compass can conceivably provide useful local orientation information indoors, even in the presence of steel structures.

## GYROSCOPES

Gyroscopes are heading sensors which preserve their orientation in relation to a fixed reference frame. Thus they provide an absolute measure for the heading of a mobile system.

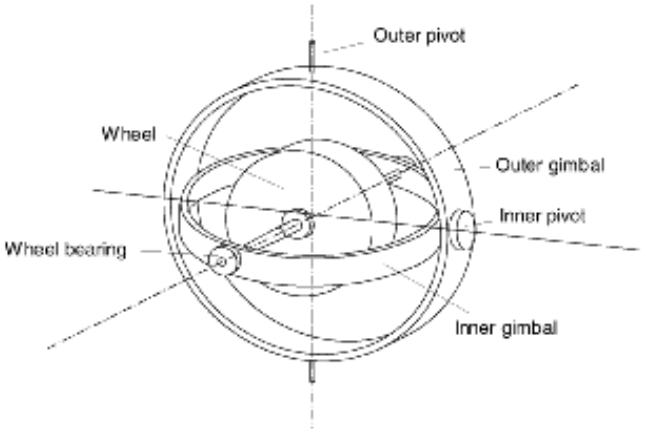



***Figure 4: Two-axis mechanical gyroscope***


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Gyroscopes can be classified in two categories, mechanical gyroscopes and optical gyroscopes.

***Mechanical Gyroscopes***

The concept of a mechanical gyroscope relies on the inertial properties of a fast-spinning rotor. The property of interest is known as the gyroscopic precession. If you try to rotate a fast-spinning wheel around its vertical axis, you will feel a harsh reaction in the horizontal axis. This is due to the angular momentum associated with a spinning wheel and will keep the axis of the gyroscope inertially stable. The reactive torque $\tau$ and thus the tracking stability with the inertial frame are proportional to the spinning speed, the precession speed □, and the wheel's inertia I.

$$\tau = I\omega\Omega \quad (5)$$

By arranging a spinning wheel, as seen in figure 4, no torque can be transmitted from the outer pivot to the wheel axis. The spinning axis will therefore be space-stable (i.e., fixed in an inertial reference frame). Nevertheless, the remaining friction in the bearings of the gyro axis introduce small torques, thus limiting the long-term space stability and introducing small errors over time. A high quality mechanical gyroscope can cost up to $100,000 and has an angular drift of about 0.1 degrees in 6 hours. For navigation, the spinning axis has to be initially selected. If the spinning axis is aligned with the north-south meridian, the earth's rotation has no effect on the gyro's horizontal axis. If it points east-west, the horizontal axis reads the earth rotation. Rate gyros have the same basic arrangement as shown in figure 4 but with a slight modification. The gimbals are restrained by a torsional spring with additional viscous damping. This enables the sensor to measure angular speeds instead of absolute orientation.

***Optical Gyroscopes***

Optical gyroscopes are a relatively new innovation. Commercial use began in the early 1980s when they were first installed in aircraft. Optical gyroscopes are angular speed sensors that use two monochromatic light beams, or lasers, emitted from the same source, instead of moving, mechanical parts. They work on the principle that the speed of light remains unchanged and, therefore, geometric change can cause light to take a varying amount of time to reach its destination. One laser beam is sent traveling clockwise through a fiber while the other


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travels counterclockwise. Because the laser traveling in the direction of rotation has a slightly shorter path, it will have a higher frequency. The difference in frequency Δf of the two beams is a proportional to the angular velocity  of the cylinder. New solid-state optical gyroscopes based on the same principle are build using microfabrication technology, thereby providing heading information with resolution and bandwidth far beyond the needs of mobile robotic applications. Bandwidth, for instance, can easily exceed 100 kHz while resolution can be smaller than 0.0001 degrees/hr.

**GROUND-BASED BEACONS**

One elegant approach to solving the localization problem in mobile robotics is to use active or passive beacons. Using the interaction of on-board sensors and the environmental beacons, the robot can identify its position precisely. Although the general intuition is identical to that of early human navigation beacons, such as stars, mountains, and lighthouses, modern technology has enabled sensors to localize an outdoor robot with accuracies of better than 5 cm within areas that are kilometers in size.

In the following section, we describe one such beacon system, the global positioning system (GPS), which is extremely effective for outdoor ground-based and flying robots. Indoor beacon systems have been generally less successful for a number of reasons. The expense of environmental modification in an indoor setting is not amortized over an extremely large useful area, as it is, for example, in the case of the GPS. Furthermore, indoor environments offer significant challenges not seen outdoors, including multipath and environmental dynamics.

A laser-based indoor beacon system, for example, must disambiguate the one true laser signal from possibly tens of other powerful signals that have reflected off of walls, smooth floors, and doors. Confounding this, humans and other obstacles may be constantly changing the environment, for example, occluding the one true path from the beacon to the robot. In commercial applications, such as manufacturing plants, the environment can be carefully controlled to ensure success. In less structured indoor settings, beacons have nonetheless been used, and the problems are mitigated by careful beacon placement and the use of passive sensing modalities.


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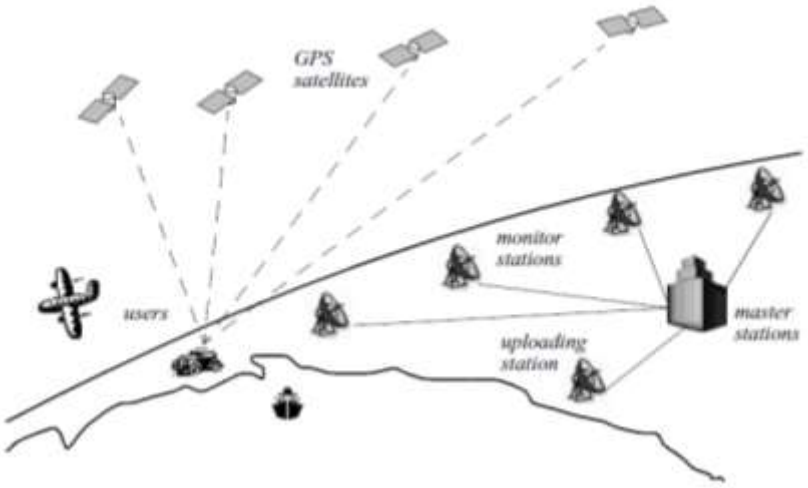



***Figure 5: Calculation of position and heading based on GPS.***

***The Global Positioning System***

The global positioning system (GPS) was initially developed for military use but is now freely available for civilian navigation. There are at least twenty-four operational GPS satellites at all times. The satellites orbit every 12 hours at a height of 20.190 km. Four satellites are located in each of six planes inclined 55 degrees with respect to the plane of the earth's equator (figure 5).

Each satellite continuously transmits data that indicate its location and the current time. Therefore, GPS receivers are completely passive but exteroceptive sensors. The GPS satellites synchronize their transmissions so that their signals are sent at the same time. When a GPS receiver reads the transmission of two or more satellites, the arrival time differences inform the receiver as to its relative distance to each satellite. By combining information regarding the arrival time and instantaneous location of four satellites, the receiver can infer its own position.

In theory, such triangulation requires only three data points. However, timing is extremely critical in the GPS application because the time intervals being measured are in nanoseconds. It is, of course, mandatory that the satellites be well synchronized. To this end, they are updated by ground stations regularly and each satellite carries on-board atomic clocks for timing.


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The GPS receiver clock is also important so that the travel time of each satellite's transmission can be accurately measured. But GPS receivers have a simple quartz clock. So, although three satellites would ideally provide position in three axes, the GPS receiver requires four satellites, using the additional information to solve for four variables: three position axes plus a time correction.

The fact that the GPS receiver must read the transmission of four satellites simultaneously is a significant limitation. GPS satellite transmissions are extremely low-power, and reading them successfully requires direct line-of-sight communication with the satellite. Thus, in confined spaces such as city blocks with tall buildings or in dense forests, one is unlikely to receive four satellites reliably. Of course, most indoor spaces will also fail to provide sufficient visibility of the sky for a GPS receiver to function. For these reasons, the GPS has been a popular sensor in mobile robotics, but has been relegated to projects involving mobile robot traversal of wide-open spaces and autonomous flying machines.

A number of factors affect the performance of a localization sensor that makes use of the GPS. First, it is important to understand that, because of the specific orbital paths of the GPS satellites, coverage is not geometrically identical in different portions of the Earth and therefore resolution is not uniform. Specifically, at the North and South Poles, the satellites are very close to the horizon and, thus, while resolution in the latitude and longitude directions is good, resolution of altitude is relatively poor as compared to more equatorial locations.

The second point is that GPS satellites are merely an information source. They can be employed with various strategies in order to achieve dramatically different levels of localization resolution. The basic strategy for GPS use, called pseudorange and described above, generally performs at a resolution of 15 m. An extension of this method is differential GPS (DGPS), which makes use of a second receiver that is static and at a known exact position. A number of errors can be corrected using this reference, and so resolution improves to the order of 1 m or less. A disadvantage of this technique is that the stationary receiver must be installed, its location must be measured very carefully, and of course the moving robot must be within kilometers of this static unit


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in order to benefit from the DGPS technique.

A further improved strategy is to take into account the phase of the carrier signals of each received satellite transmission. There are two carriers, at 19 cm and 24 cm, and therefore significant improvements in precision are possible when the phase difference between multiple satellites is measured successfully. Such receivers can achieve 1 cm resolution for point positions and, with the use of multiple receivers, as in DGPS, sub-1 cm resolution.

A final consideration for mobile robot applications is bandwidth. The GPS will generally offer no better than 200 to 300 ms latency, and so one can expect no better than 5 Hz GPS updates. On a fast-moving mobile robot or flying robot, this can mean that local motion integration will be required for proper control due to GPS latency limitations.

**CONCLUSION**

We can summarize the effects of the parameters on the sensor accuracy as follows:

- Baseline length ( ): the smaller is, the more compact the sensor can be. The larger is, the better the range resolution will be. Note also that although these sensors do not suffer from the correspondence problem, the disparity problem still occurs. As the baseline length is increased, one introduces the chance that, for close objects, the illuminated point(s) may not be in the receiver's field of view.

- Detector length and focal length ( ): A larger detector length can provide either a larger field of view or an improved range resolution or partial benefits for both. Increasing the detector length, however, means a larger sensor head and worse electrical characteristics (increase in random error and reduction of bandwidth). Also, a short focal length gives a large field of view at the expense of accuracy, and vice versa.

At one time, laser stripe-based structured light sensors were common on several mobile robot bases as an inexpensive alternative to laser range finding devices. However, with the increasing quality of


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laser rangefinding sensors in the last few decades, the structured light system has become relegated largely to vision research rather than applied mobile robotics.

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