W. John Ballantyne. "Distance."

Distance

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The tools and techniques of distance measurement are possibly one of humankind's longest-running inventive pursuits. The scale shown in Figure 9.1 illustrates the enormous range of distances that science and engineering have an interest in measuring [1]. This chapter concerns itself with methods to measure a relatively small segment of this range — from centimeters to kilometers. Even within this limited segment, it would hardly be possible to list, much less describe, all of the distance measurement approaches that have been devised. Nevertheless, the small sampling of technologies that are covered here should be of help to a broad range of readers.

Distance measurement, at its most basic, is concerned with determining the length of a unidimensional line joining two points in three-dimensional space. Oftentimes, a collection of distance measurements is called for, so that the shape, the orientation, or the changes in position of an object can be resolved. Therefore, one must consider not only the measurement of distances, but also their spatial and temporal distributions. The terminology "ranging" will be used in reference to systems that perform single sensor-to-target measurements, "range-imaging" for systems that collect a dense map or grid of spatially distributed range measurements, and "position tracking" for systems that record the time history of distance measurement to one or several targets.

9.1 Basic Distinctions Between Range Measurement Techniques

Range measurement devices may be classified according to some basic distinctions. Generalizations can be made based on these broad classes, thereby facilitating the process of comparison and selection. The following subsections identify the fundamental bases for classification.

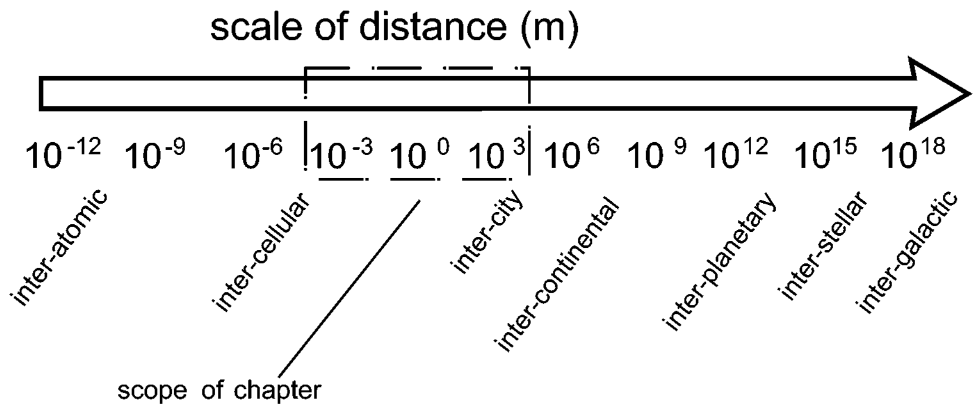

FIGURE 9.1 From the interatomic to the intergalactic, the range of measurable distances spans at least 30 orders of magnitude. The box outline indicates the relatively small segment that concerns this chapter.

Contact or Noncontact

A common approach to measuring the distance to a point on an object is through a calibrated mechanical device that simultaneously connects the selected point to a reference position. Any tape measure, feeler gage, or dial gage may be considered an example of a simple contacting measurement device. Mechanical/electronic devices are available that allow a user to "digitize" discrete point positions on a three-dimensional surface. A gimbaled probe on the end of an *X-Y-Z* positioner or articulated arm is used to touch a specific point, and sensory information of the linear positions or joint articulations provide an accurate position estimate. Mechanical, contact-based methods are widely used in industry and can be extremely accurate. Some coordinate measuring machines (CMMs), for example, can achieve 1 μm repeatability.

The chief disadvantage of mechanical approaches is that they are usually restricted to distances and work volumes up to a few meters at maximum.This is due to fundamental scaling laws for mechanical structures. As the requirement to span larger distances increases, the mass and mechanical tolerancing requirements on the machine make designs impractical. Also, mechanical approaches are too slow to make multiple measurements in rapid succession, as is typically required in range imaging or position tracking, when the measurement involves large sets of spatially or temporally distributed data.

Noncontact techniques for performing ranging, range imaging, and position tracking are many and varied. Besl [2] reviews and compares several of these. In the centimeters to meters range, most do not approach the accuracy of CMMs; but at larger scales and for large quantities of data, they become a practical necessity. The rest of this chapter will review noncontact approaches only.

Active or Passive

Noncontact distance measurement may be divided into *active* or *passive* techniques. Active techniques involve some form of controlled energy (field or wave) linking a known reference location to the unknown target location. The source of energy is typically associated with the reference location, but in some cases the target, or both target and reference, may be active. Passive techniques rely on an externally occurring source of energy (e.g., sunlight or target/background temperature contrast) to make the target detectable.

An active approach can often simplify the distance measurement problem because it allows a greater degree of control over the many factors that can influence a measurement. For example, the choice of the form of energy and the power level of the active source can minimize the effect of uncontrolled variables like ambient illumination, weather, and atmospheric conditions. Furthermore, an active approach provides an opportunity to selectively localize the measurement spatially and temporally, eliminating possible ambiguity about which target point was measured at a given time. In contrast, passive systems (e.g., stereo ranging) sometimes suffer from the so-called "correspondence problem," which is concerned with how to determine whether a given target point, detected from two or more viewpoints, or over two or more instants, is in fact the same physical point.

A common use of active approaches is to make range measurements "through" materials that are mechanically or optically impenetrable. Examples include medical imaging, where various forms of directed energy (ultrasound, X-rays) are used to build surface or volumetric maps of organs and bones; sonar, which penetrates water better than light does; and ground-penetrating radar, which can detect objects and their depth beneath ground surface.

Passive approaches, while not offering the same range of control and flexibility of active approaches, offer certain advantages. First, because they emit no energy, their existence cannot be detected by another remote detection system. This feature is very important in military applications. Second, passive systems can often collect multiple point range measurements more quickly because they are not limited by the rate at which they can direct an energy source toward a target point, as is the case with most active systems. For example, a stereo ranging system effectively collects all resolvable target points in its field of view simultaneously, while a scanning laser, radar, or sonar ranging system collects each measured point sequentially. Finally, the absence of a directed energy source is a simplification that can significantly reduce the size, cost, and hardware complexity of a device (although at the expense of increased signal processing complexity).

Time-of-Flight, Triangulation, or Field Based

There are many different classes and instances of noncontact ranging devices, but with very few exceptions they are based on one of the following three basic principles:

1. Energy propagates at a known, finite, speed (e.g., the speed of light, the speed of sound in air)
2. Energy propagates in straight lines through a homogeneous medium
3. Energy fields change in a continuous, monotonically decreasing, and predictable manner with distance from their source

The techniques associated with these basic phenomena are referred to as time-of-flight, triangulation, and field based, respectively.

Time-of-Flight

Time-of-flight (TOF) systems may be of the "round-trip" (i.e., echo, reflection) type or the "one-way" (i.e., cooperative target, active target) type. Round-trip systems effectively measure the time taken for an emitted energy pattern to travel from a reference source to a partially reflective target and back again. Depending on whether radio frequencies, light frequencies, or sound energy is used, these devices go by names such as radar, lidar, and sonar. One-way systems transmit a signal at the reference end and receive it at the target end or vice versa. Some form of synchronizing reference must be available to both ends in order to establish the time of flight.

A characteristic of many TOF systems is that their range resolution capability is based solely on the shortest time interval they can resolve, and not the absolute range being measured. That is, whether an object is near or far, the error on the measurement is basically constant.

Triangulation

Triangulation techniques were known and practiced by the Ancients. Triangulation is based on the idea that if one knows the length of one side of a triangle and two of its angles, the length of the other sides can be calculated. The known side is the "baseline." Lines of detection extend from either end of the baseline to the target point as shown in Figure 9.2. If the angles formed between these lines and the baseline can be determined, the distance is calculated as:

$$R = b \sin\alpha_{\text{left}} \sin\alpha_{\text{right}} \Big/ \sin\left(\alpha_{\text{right}} - \alpha_{\text{left}}\right) \tag{9.1}$$

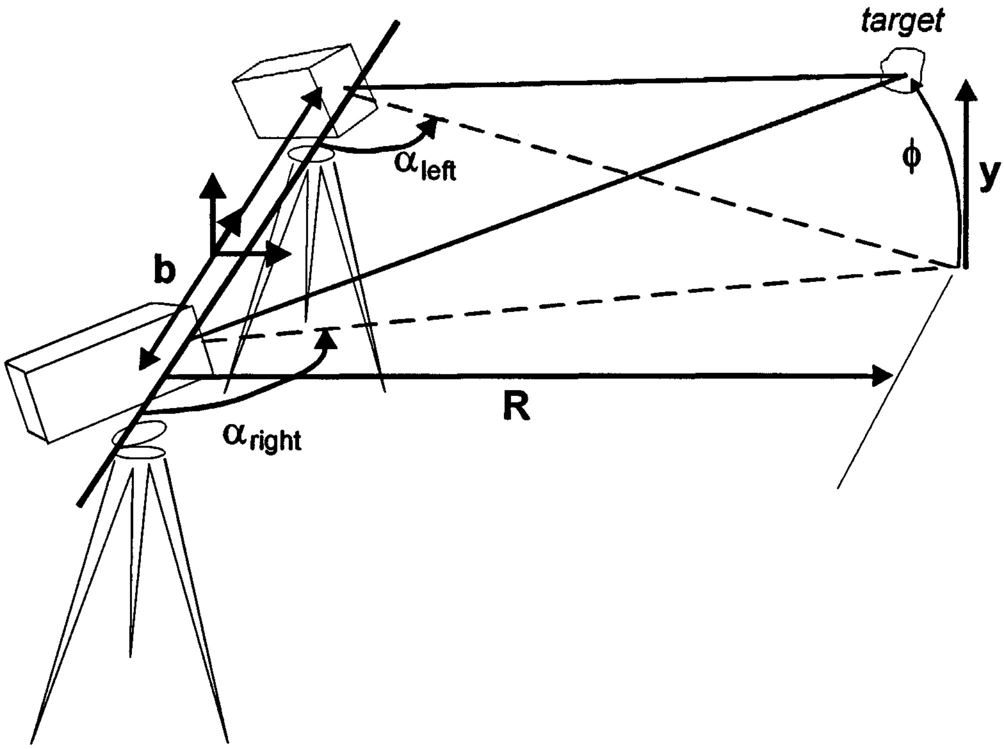

FIGURE 9.2 The basic triangulation geometry as used in classical surveying determines the distance to a remote point by sighting it from two locations separated by a known baseline. The pointing angles α_{left} and α_{right} are measured locally.

Classical surveying is a passive range-finding technique based on the above formula. A surveyor uses a precision pointing instrument to sight a target from two positions separated by a known baseline. Reference [3] notes that the distance to a nearby star may be calculated by observing it through a pointing instrument at 6-month intervals and using the diameter of Earth's solar orbit as the baseline. Stereo ranging, which compares the disparity (parallax) between common features within images from two cameras, is another form of passive triangulation. It is of interest to note that human vision estimates distance using a variety of cues, but two of the most important — stereopsis and motion parallax — are fundamentally triangulation based [4].

Active triangulation techniques use a projected light source, often laser, to create one side of the triangle, and the viewing axis of an optical detection means to create the second side. The separation between the projector and detector is the baseline.

A fundamental issue for all triangulation-based approaches is that their ability to estimate range diminishes with the square of the range being measured. This may be contrasted with TOF approaches, which have essentially constant error over their operating range. Figure 9.3 illustrates how, conceptually, there is a "crossover" distance where TOF techniques become preferable to triangulation techniques.

Field-Based Approaches

Whereas TOF and active triangulation techniques employ the wave propagation phenomena of a particular energy form, *field-based* approaches make use of the spatially distributed nature of an energy form. The intensity of any energy field changes as a function of distance from its source. Moreover, fields often exhibit vector characteristics (i.e., directionality). Therefore, if the location of a field generator is known and the spatial characteristics of the field that it produces are predictable, remote field measurements contain information that may be used to infer distance from the source.

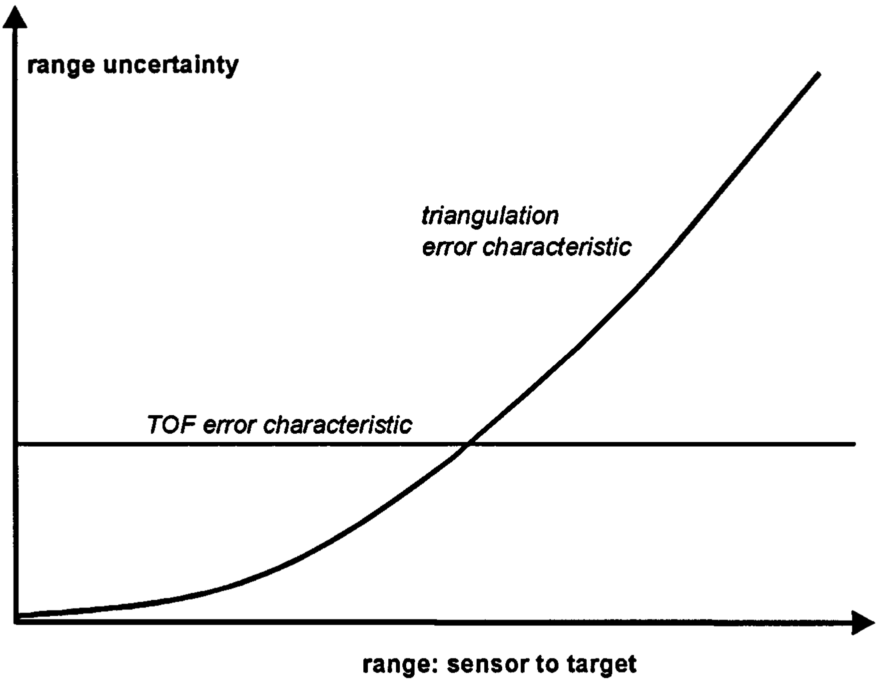

FIGURE 9.3 Time-of-flight (TOF) and active triangulation techniques tend to exhibit error characteristics related to their fundamental principles of operation. The dominant error source in TOF systems is usually the shortest measurable time interval, but this is a detection issue and is essentially independant of distance. Active triangulation systems are typically more accurate at close distances, but geometry considerations dictate that the effects of their error sources will increase with the square of distance.

An interesting distinction between field-based approaches and wave-based approaches is that the former, although they employ energy fields, do not rely on the propagation and conversion (and concomitant losses) of energy. That is, they may employ stationary fields, like those generated by a magnet or static charge. Such fields encode position information by their very shape. Sound and light, although having a wave nature, can be exploited in the same manner as stationary fields because of their distance-dependent intensity.

Field-based techniques must confront some basic issues that limit their range of application. First, the characteristics of most practically exploitable fields are typically influenced by objects or materials in the vicinity, and it is not always possible to ensure that these influences will remain constant. Second, the variation of fields through space is highly nonlinear (typically inverse square or inverse cube), implying that the sensitivity of a measurement is strongly affected by proximity to the source. Notwithstanding these concerns, devices have been developed and are available that perform very well in the situations for which they are intended [7].

Form of Energy

As discussed above, all noncontact, active ranging devices employ some form of energy. This is true whether time-of-flight, triangulation, or field-based principles apply. The following subsections describe the various forms of energy employed and some generalizations about the effectiveness of each in various situations.

Sound

Ranging systems based on sound energy are usually of the pulsed-echo TOF type and employ carrier frequencies in the so-called "ultrasonic" (beyond audible) range of frequencies. Besides being inaudible (an obvious benefit), ultrasonic frequencies are more readily focused into directed beams and are practical to generate and detect using piezoelectric transducers. Ultrasonic signals propagate through air, but long-distance transmission is much more effective in liquids, like water, where higher density-to-viscosity ratios result in higher wave velocity and lower attenuation per unit distance. Ultrasonic ranging techniques (or SONAR, for SOund NAvigation and Ranging) were first developed for subsea applications, where sound is vastly superior to electromagnetic energy (including light) in terms of achievable underwater transmission distances [5]. Low-cost, portable sonar systems are widely used by sport fisherman as "fish finders" [6].

The frequencies typically used in sonic ranging applications are at a few tens of kilohertz to a few hundred kilohertz. A basic trade-off in the choice of ultrasonic frequency is that while high frequencies can be shaped into narrower beams, and therefore achieve higher lateral resolution, they tend to fade more quickly with distance. It may be noted that beam widths narrow enough for range imaging applications (less than 10°) are effective in a fluid medium, but attenuate too quickly to be practical in air. Interestingly, although sound energy attenuates more rapidly in air than in water, useful short-range signals can be generated in air with relatively low power levels because the much lower density of air requires smaller dynamic forces in the transducer for a given wave amplitude.

When comparing sound energy to electromagnetic energy for TOF-based techniques, one needs to remember that sound, unlike light, propagates at not only much lower speeds, but with considerably more speed variation, depending on the type and state of the carrying media. Therefore, factors like air humidity and pressure will affect the accuracy of a TOF ranging device. For underwater applications, salinity and depth influence the measurement. The lower speed of sound has a detrimental impact on the rate at which range samples can be collected. For example, a target 10 m away takes at least 60 ms to measure through an air medium. This may not seem like a long time to wait for a single sample, but it becomes an issue if the application involves multiple sampling, as in motion tracking or collision avoidance sensing.

Stationary Magnetic Fields

Stationary or pseudostationary (i.e., low frequency) magnetic fields are only used in field-based approaches. An advantage of such fields is that they are easily and cheaply produced by either a permanent magnet or electrical coil. Since stationary fields do not transmit energy, the targets cannot be passive — they must actively sense the properties of the field at their particular location. A variety of sensing technologies may be used to make measurements of the direction and intensity of a magnetic field, including flux gate, Hall effect, and magnetostrictive type magnetometers. A comprehensive list of such technologies is given in [7].

Radio Frequencies

Echo-type TOF ranging systems based on the band of the electromagnetic spectrum between approximately 1 m and 1 mm wavelength are known as RADAR (RAdio Detection And Ranging). Radio waves can be used for long-distance detection in a variety of atmospheric conditions. As in the case of sound waves, there are trade-offs to be addressed in the choice of frequency. Long waves tend to propagate better over long distances, but short waves can be focused into narrow beams capable of better lateral discrimination. An interesting application of short-range radar is ground-penetrating radar, which can be used to locate and image subsurface objects [8]. Here, the frequency vs. range trade-off is particularly acute because of the need to balance reasonable imaging capability (narrow beam) with good depth penetration (long wave).

An example of a TOF one-way (active receiver) system that uses radio frequencies is the global positioning system (GPS). The distance between a receiver on land is determined by each of several orbiting satellites equipped with a transmitter and a very precise Cesium clock for synchronization. A good description of GPS and its use in vehicle navigation is available in [9].

Light Frequencies

Beyond the radio portion of the electromagnetic spectrum are the infrared, visible, and ultraviolet frequencies. These frequencies can be produced by lasers and detected by solid-state photosensitive devices and are useful for both TOF and active triangulation ranging. Echo-type TOF techniques are known as LIDAR (LIght Detection And Ranging), in keeping with the terminology introduced earlier.

While light frequencies attenuate more than radio frequencies through cloud and fog, they can have very narrow beam widths, allowing superior lateral resolution and target selectivity.

Coherent or Noncoherent Detection

Echo-type TOF devices, whether sonar, radar, or lidar, can be further classified according to whether the detection approach measures time-of-flight directly (noncoherent) or exploits an inherent periodicity in the emitted energy to ascertain the flight distance (coherent).

Noncoherent techniques face the problem of timing short intervals. This is not a serious challenge in the case of sound waves, where a meter round trip corresponds to 6 ms, but is somewhat more problematic for light and radio waves, where that distance equates to only 6 ns. Accuracy of noncoherent detection typically relies on the averaging of repeated measurements.

Coherent detection is achieved by combining a portion of the emitted signal with the reflected signal to produce a third signal indicating the amount of phase delay. The signals are continuous wave (CW) as opposed to pulsed. Coherent detection techniques are classified as amplitude modulated (AMCW) or frequency modulated (FMCW).

A basic issue with coherent detection techniques is the inability to distinguish between integral multiples of the basic modulation wavelength. Any coherent detection system must employ techniques to resolve the so-called "ambiguity interval." Noncoherent techniques do not face this problem.

Ranging, Range Imaging, or Position Tracking

Ranging devices are typically pointed toward a target to produce a single range reading. A common example of simple ranging is the feedback sensor used in auto-focus cameras. There are many active ranging devices currently available based on TOF (i.e., radar, sonar, lidar) and active triangulation principles.

Range imaging devices use the same principles as ranging devices, except that they include some form of scanning that is employed to generate an array of spatially distributed range samples. Sometimes, the scanning action is accomplished by means intrinsic to the sensor (e.g., spinning and nodding mirrors, or phased-array antenna) so that the reference location remains fixed. In this case, the data are recorded in the polar form (range, elevation, azimuth) as shown in Figure 9.4. In other cases, the sensor might scan on only one axis internally while the second scan dimension is realized by moving the sensor location through some set pattern. It is not uncommon to record the "intensity" or return energy associated with a range sample as well. The intensity map may be presented as a "gray scale" image and, like a black and white photograph, often contains additional information useful in interpreting a scene. Range images can be used to produce three-dimensional graphic representations of scenes and objects. A common use of range imaging is aerial terrain mapping.

Position tracking devices are used to measure the change in an object's position and orientation over time. Basic issues in position tracking are the acquiring of, and locking on to, specific target points. These issues can be avoided by employing active targets, and most systems available today are of this type.

9.2 Performance Limits of Ranging Systems

The performance characteristics of available ranging systems vary widely, as do the requirements of the applications for which they are designed. The following subsections review the most basic performance categories and the technical issues of performance limits.

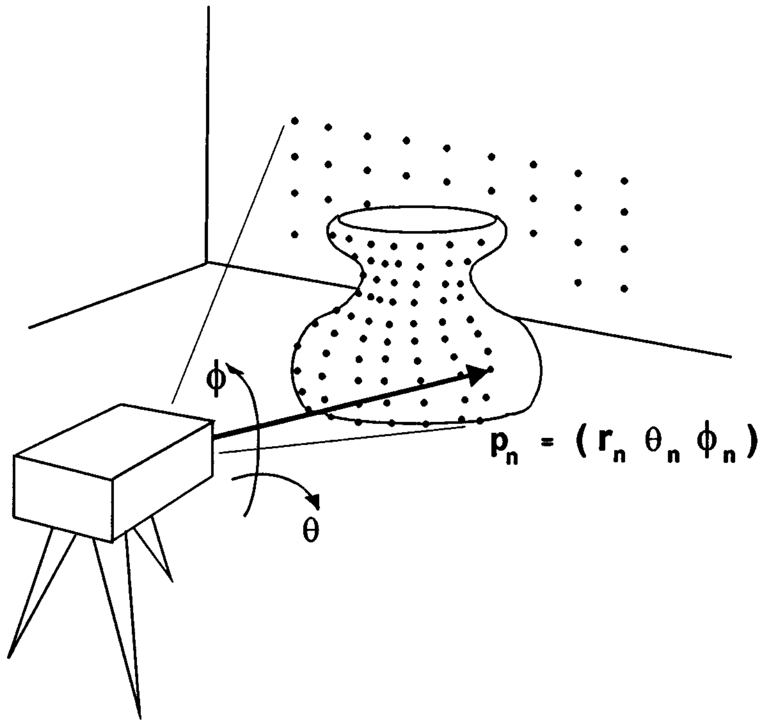

FIGURE 9.4 Range images are typically an array of individual range values sampled while changing the pointing direction (e.g., azimuth and elevation angles) of a ranging device. A digital range image of the polar form shown can be readily transformed into rectangular coordinates if required.

Range Accuracy

As illustrated in Figure 9.3, TOF and active triangulation techniques differ fundamentally in their error vs. distance characteristics. Currently available systems based on active triangulation achieve better repeatability and accuracy in the less than 1 m range than do TOF systems, but are seldom used at distances of several meters. Hymarc Ltd. and Perceptron Inc. each offer laser triangulation systems with 3σ accuracy of 25 mm and 50 mm, respectively [10, 11].

In principle, TOF systems could achieve accuracy rivaling active triangulation, but the most promising detection technique — a variation of laser interferometry, which solves the ambiguity interval problem [12] — has yet to make its commercial debut.

Depth of Field

Depth of field refers to the interval of distance through which a stationary reference ranging system can measure without resorting to a change in configuration. Large depth of field is often an important characteristic in practical applications. For example, if the distance to the target is poorly known a priori, then a large depth of field is desirable.

Passive optical triangulation approaches like stereography and photogrammetry tend to have restricted depth of field because they rely on camera-type imaging, which is inherently limited by depth of focus. Timed-interval TOF systems have excellent depth of field because they do not rely strongly on optical imaging except to concentrate the collected return energy on the detector. Some active triangulation systems do rely on optical imaging of the projected laser spot, but the design employed by Hymarc Ltd. regains a large depth of field by tilting the detector array with respect to the lens plane [13].

Maximum Range

Any active ranging, range imaging, or position tracking system has a practical maximum distance that it can measure. This is because the controlled energy, whether propagated as a wave or established as a field, must spread before reaching the detector. The spreading inevitably increases with distance and all detectors, no matter what form of energy they measure, require a certain minimum amount to exceed their inherent "noise floor."

The "classical radar range equation" is introduced in many texts on radar (e.g., [14]). Jelalian [15] points out that the equation is equally applicable to lidar, which, after all, just employs a higher frequency version of electromagnetic wave. In fact, the same idea applies to sonar and to active triangulation systems as well. The equation computes the power of the received signal as:

$$P_R = P_T G_T \big/ 4\pi R^2 \times \rho A \big/ 4\pi R^2 \times \pi D^2 \big/ 4 \times \eta_{atm} \eta_{sys} \qquad (9.2)$$

where P_R = power at the receiver
P_T = power transmitted
G_T = transmitter gain
R = range to target
ρ = reflectivity of target
A = effective area of target
D = diameter of collecting aperture
η_{atm} = atmospheric transmission coefficient
η_{sys} = system transmission coefficient

Equation 9.2 applies when the target area is smaller than the footprint of the incident beam, which is often the case for radar and sonar ranging. However, in the case of laser-based systems, the relatively narrow beam usually means that the laser spot is small compared to the target. For a transmitted beam that spreads with a solid angle θ_T, the illuminated patch area is:

$$\sigma_{spot} = \pi R^2 \theta_T^2 \qquad (9.3)$$

The definition of transmitter gain is based on the notion of the solid angle beam width as compared to an omnidirectional transmitter

$$G_T = 4\pi \big/ \theta_T^2 \qquad (9.4)$$

One can substitute for Equation 9.4 for G_T and Equation 9.3 for the variable s in Equation 9.2 to produce the range equation for a small spot size.

$$P_R = P_T \big/ R^2 \times \rho \big/ 4 \times \pi D^2 \big/ 4 \times \eta_{atm} \eta_{sys} \qquad (9.5)$$

The importance of this equation is primarily in the $1/R^2$ dependence. Any ranging system that works by bouncing energy off a diffuse reflective target encounters severe signal attenuation with increasing distance. Given a detector with a fixed noise floor, the only ways to improve maximum range are to increase the transmitted power or the collecting area. In practice, there are design constraints that limit both of these measures. For example, laser power must sometimes be limited for eye-safety considerations, and increased collecting area can imply a proportional increase in sensor packaging volume.

Lateral Resolution

In range imaging applications, it is generally desirable to use the narrowest possible beam width to provide good lateral discrimination of target surface features. Lasers, because of their short wavelength, can be optically collimated to produce much narrower beam widths than are possible with radio sources. However, even lasers cannot produce arbitrarily narrow beams. The interested reader is referred to [13] for a discussion of Gaussian beam propagation and optimal focusing. There are basically two ways to project laser light. The beam can be "focused down" to produce the smallest possible spot at a particular point inside the measurement range, in which case the beam will diverge as the distance from that point increases; or the beam can be focused at infinity or some very distant point so as to minimize the divergence through the entire measurement range. The former approach provides higher lateral resolution at the focus distance, but by implication restricts the practical depth of field. The latter compromises spot size for increased depth of field.

Rate of Acquisition

The rate at which a ranging sensor can acquire range samples is important when the target object is changing shape or position, or when the required sample density of a range image is very high. There are several potential factors that can limit sample acquisition rate: the amount of time required by the detector to integrate the weak return signal to a sufficient level (integration time); the time constant of any filtering or averaging that must be performed to realize an acceptably "clean" signal (smoothing time); the rate at which samples can be transferred through the signal processing stages (transfer time); and the velocity limits of mechanical scanning apparatus (scanning bandwidth). Acquisition rates vary widely: from tens of hertz for acoustic ranging devices to tens of kilohertz for some laser-based systems. It is worth noting that, in general, there is a trade-off between rate of acquisition, accuracy, and maximum range. Some systems permit control over basic parameters so that this trade-off may be optimized for a particular application. The reader should be aware that data sheets may not be clear as to whether stated performance figures for these three specifications are valid in combination.

9.3 Selected Examples of Ranging, Range Imaging, and Motion Tracking Systems

The following sections review selected examples of some specific ranging, range imaging, and position tracking sensor systems. The list is by no means exhaustive, but offers a reasonable sampling of available technologies.

Laser-Based Active Triangulation Ranging and Range Imaging Sensors

Active Triangulation Basics

Figure 9.5 illustrates the basic active triangulation geometry. In this so-called "pinhole camera" model, practical aspects like lenses for projection and detection and mirrors for scanning are eliminated for clarity. It can be shown by means of similar triangles that the range is inversely proportional to the deflection of the imaged spot.

$$R = bf/u \tag{9.6}$$

where R = distance to object
b = baseline distance
f = lens to detector distance
u = detected spot position in the image plane

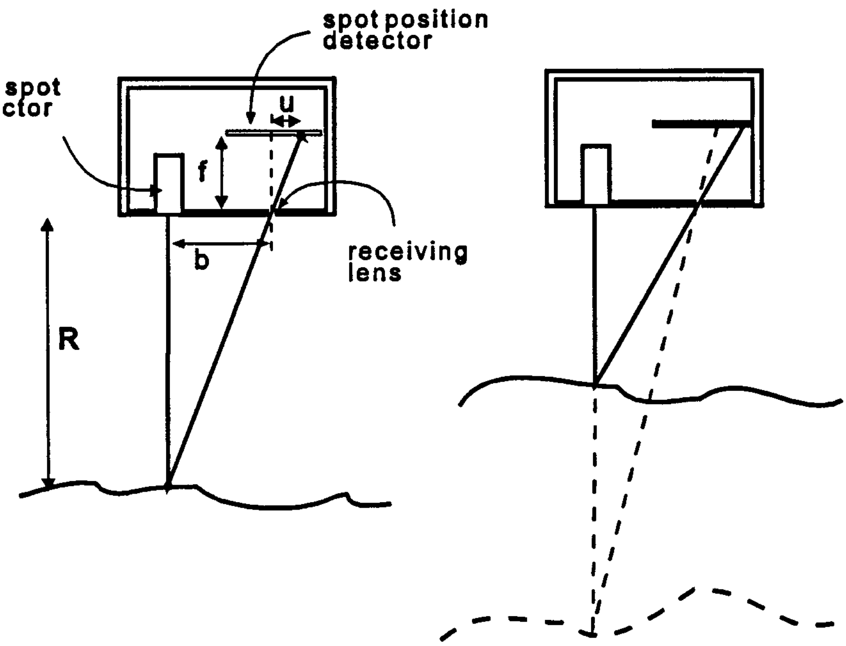

FIGURE 9.5 A simple pinhole camera model illustrates the basic active triangulation principle. As the distance R to the target surface changes, the spot position u on the detector changes, maintaining similarity between the large triangle outside the camera and the small triangle inside. There is an inverse relationship between R and u.

The sensitivity of the range measurement, or the incremental change in u with R, is

$$\left| du/dR \right| = bf/R^2 \tag{9.7}$$

The significance of Equation 9.7 is that range estimating performance is expected to fall as distance increases. Improvements in accuracy are realized by increasing the baseline or the lens to detector distance (i.e., the focal length).

Synchronized Scanning Principle

Lateral scanning of an active triangulation ranging sensor is accomplished by an elegant and effective technique developed at Canada's National Research Council and now marketed by Hymarc Ltd. under the name "HYSCAN" [10]. A two-sided oscillating mirror simultaneously steers the outgoing beam on one face and directs the collected light to the spot-imaging optics on the opposite face. By synchronously scanning both the beam and the axis of the detection system, rather than the beam only, as conventionally practiced, significant performance improvements are made. Figure 9.6 is a schematic illustration of the approach. Note also that the detector plane is tilted with respect to the lens plane. This feature increases the depth of focus so that the ranging performance is maximized over the measuring volume. The Hyscan sensor produces a single-axis sweep, or so-called "line scan." Full-dimension range images are acquired by translating the sensor over a target surface with a controlled motion pattern.

Light Plane Principle

Perceptron Inc. offers a similar line-scan system under the name "TriCam" [11]. In this case, the laser is not swept. Instead, the beam is transformed to a focused plane by means of cylindrical lenses. A two-dimensional detector is used to generate range profiles through the analysis of a deformation of the laser line as the sensor is translated over the object surface.

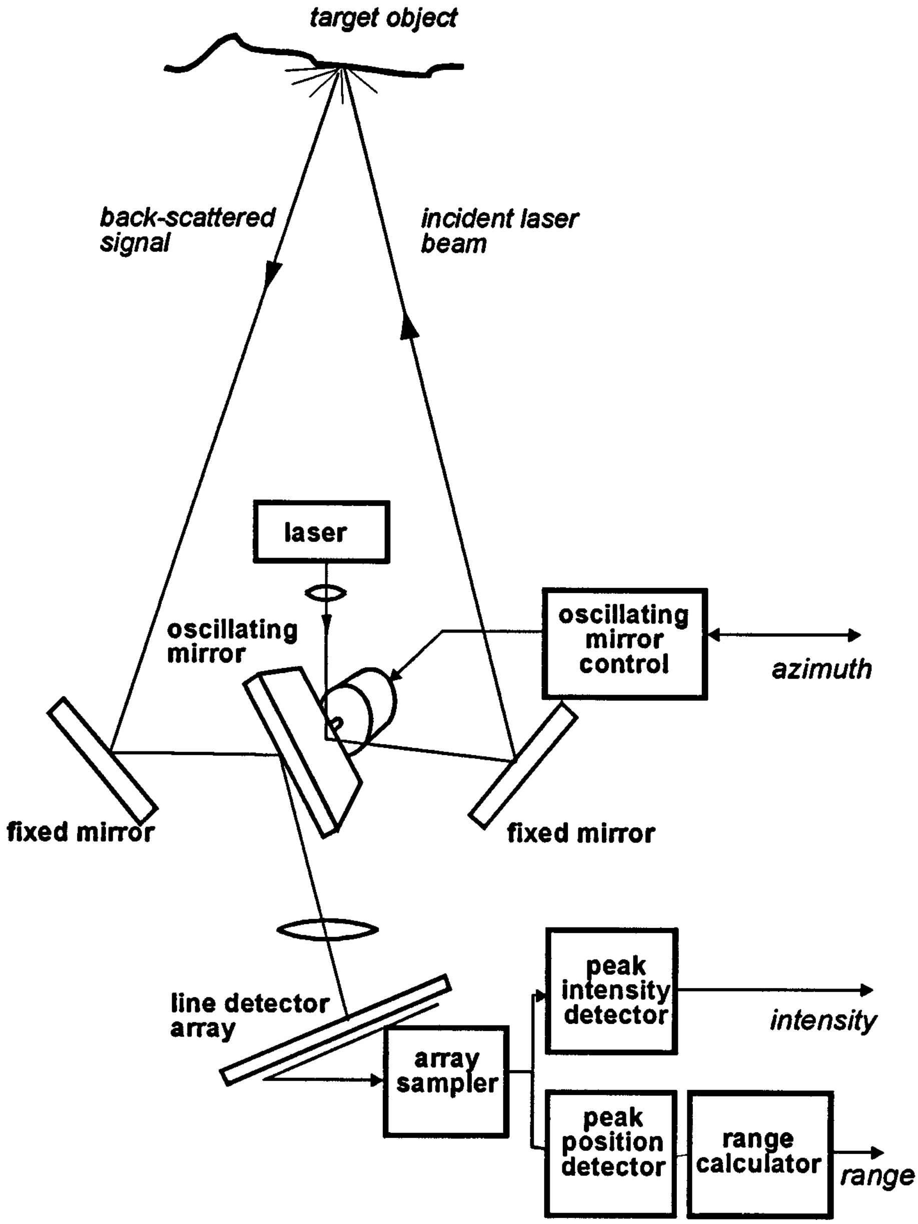

FIGURE 9.6 The Hymarc laser triangulaton line scanner uses the synchronized scanning principle. Both sides of an oscillating mirror are used to sweep both the projected beam and the axis of detection over the target. The detector array is tilted to the lens plane to maximize the depth of focus.

Laser-Based Lidar Range Imaging Sensors

AM Lidar (Phase-Based Detection)

Perceptron Inc. also offers a scanning lidar under the name "LASAR" that can produce high-resolution range images through a large measurement volume. The device uses a near-infrared laser that is projected through a collimating telescope to form a spot on the first surface encountered. The spot is swept over

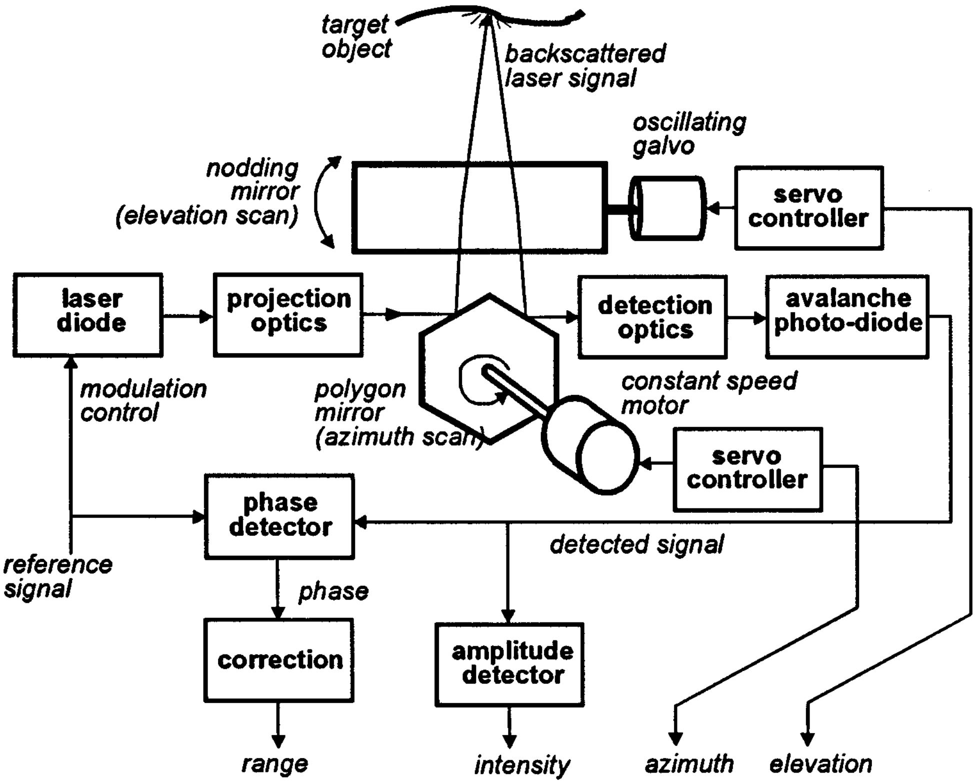

FIGURE 9.7 The Perceptron AM Lidar system described in U.S. patent 5,006,721 uses a rotating polygon mirror for synchronized scanning. A "nodding mirror" is also added to sweep at a slower rate in the orthogonal direction, producing a raster scan pattern. Range measurement is determined by comparing the phase of the outgoing and returning AM laser signal.

a programmable field of view in a raster pattern by means of a spinning polygon mirror and an oscillating "nodding mirror." Some of the backscattered light is collected and directed by means of an adjacent facet of the polygon mirror. The projected laser light is amplitude modulated at a reference frequency by controlling the power to the laser diode source. The return signal, although orders of magnitude weaker than the outgoing signal, is phase-compared to determine the range for a particular azimuth and elevation. The intensity of the return energy is also recorded. The Perceptron sales literature claims a maximum measurement volume of 60° × 72° × 40 m, a range image grid resolution of 1024 × 2048 pixels and a maximum acquisition rate of 360,000 pixels/s. A schematic diagram of the LASAR™ system is shown in Figure 9.7. Details of the Perceptron technical approach may be found in [16].

Resonating Lidar (Frequency-Based Detection)

Acuity Research Inc. has developed a laser-based TOF ranging sensor based on a simple but effective idea. The detector controls the laser output such that the absence of a signal drives the laser on and the presence of a signal turns it off. The finite transit time of the light bounce turns this arrangement into a two-state resonator, with the period being proportional to the target distance. Rather than measuring the period, which is extremely short and difficult to time, the frequency is measured using conventional counting techniques for as many cycles as necessary to yield the required accuracy. The AccuRange 4000, as it is named, is also available in a 360° line-scanning arrangement suitable for robotic vehicle navigation applications [17]. Details of the technical approach may be found in [18].

Position Tracking with Active Targets

Active target approaches are not convenient in some applications, but they are an excellent way to track the changing positions of several target points simultaneously. Active targets are a way of getting around the "correspondence problem" mentioned earlier. The two systems introduced here are interesting to compare. One employs light energy and triangulation; the other uses a magnetic field-based approach. They are both used for real-time tracking and recording of human kinetics, robotics, and other moving objects.

Active Target Triangulation

The "OPTOTRAK" system offered by Northern Digital Ltd. [19] uses infrared light emitting diodes (LEDs) as targets. The LEDs are multiplexed so that only one at a time can be seen by the camera system, avoiding the correspondence problem. The unique form of stereo ranging is based on three line detectors with lenses that transform the point source LED illumination into a focused line. The simplified triangulating geometry is shown in Figure 9.8. It may be shown from this geometry that the target position (x_p, y_p, z_p) can be determined from the detector outputs u_{left}, u_{right}, and v as follows:

$$x_p = b\left(u_{right} + u_{left}\right) \Big/ 2\left(u_{right} - u_{left}\right) \tag{9.8}$$

$$y_p = bv \Big/ \left(u_{right} - u_{left}\right) \tag{9.9}$$

$$z_p = fb \Big/ \left(u_{right} - u_{left}\right) \tag{9.10}$$

where f and b are the lens-to-detector distance and the baseline separation respectively. In practice, the image space to object space mapping is much more complicated than Equations 9.8 to 9.10, and involves a camera model with more than 60 parameters that are determined through a calibration process.

OPTOTRACK offers high sampling rate, large measurement volume, and high accuracy compared to many other position tracking systems.

Magnetic Position Tracking

A position/orientation tracking sensor based on a three-axis magnetic dipole transmitter and a three-axis magnetic loop detector has been developed by Polhemus Inc. [20]. The transmitted fields are alternating current for ease of detection (i.e., transformer coupled) and time-multiplexed so that the field due to each axis can be distinguished from the others. Distance between transmitter and detector is determined by exploiting the $1/R^3$ relationship between field strength and distance from the source. Orientation of the detector is determined by exploiting the directionality of magnetic fields and the direction sensitivity of loop detectors.

An issue with respect to the use of ac fields is the distortions in field shape that occur if metal objects are present, and the consequent effect on sensor accuracy. These distortions result from eddy currents in the conducting metal. Ascension Technology Corp. has developed a variation on the Polhemus sensor based on dc magnetic fields. The switching transient due to time-multiplexing does produce an eddy current effect, but it is allowed to die out before measurement is made. Details of the dc technique are available in [21].

An important difference between optical and magnetic tracking technologies is that the former require an unbroken line of sight to the targets while the latter do not. This gives magnetic trackers an advantage in some applications. On the other hand, the $1/R^3$ field distribution characteristic of magnetic tracking

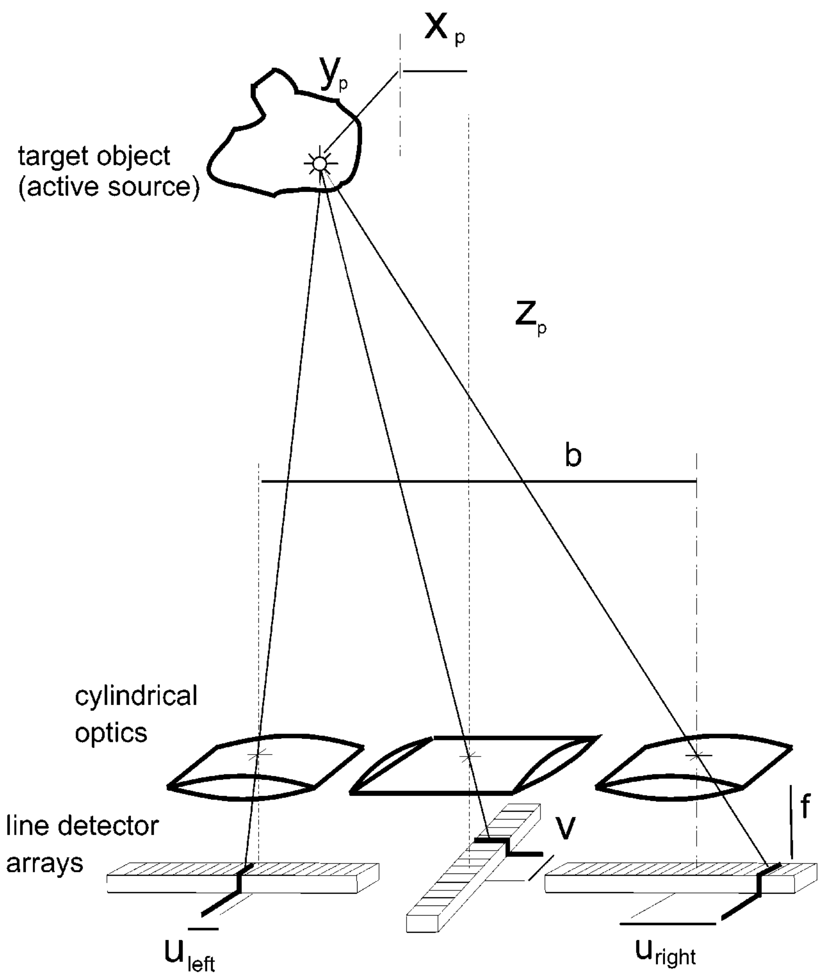

FIGURE 9.8 The OPTOTRAK position tracking system employs a novel arrangement of cylindrical optics and one-dimensional detectors to triangulate the 3-D position of an infrared LED target. Up to 255 individual multiplexed targets can be tracked by the system.

implies an extreme sensitivity loss with distance, whereas optical triangulation has a more benign $1/R$ characteristic. This, to some extent, explains why the volume of measurement and accuracy of optical triangulation systems is generally much better than for magnetic systems.

9.4 A Sampling of Commercial Ranging, Range Imaging, and Motion Tracking Products

Table 9.1 contains information collected from vendor literature. Be advised when comparing specifications that test conditions, standards, and interpretations can vary significantly. The specifications, therefore, should serve only as a rough guide.

TABLE 9.1 Ranging, Range Imaging, and Position Tracking Products and Vendors

Class	Trade Name	Principle	Features	Contact
Ranging (contact)	MicroScribe-3DX	Instrumented arm	50 in. spherical work volume, 0.3 mm accuracy	Immersion Corp. (408) 467-1900, info@immerse.com
Ranging (noncontact)	LASERVISION	TOF, laser	50 m range, 4.9 mm accuracy @ 15 m, integrated electronic level	ZIRCON Corp., (408) 866-8600
Range-Imaging (line scan)	HYSCAN	Active triangulation laser	40 mm depth of field, 70 mm swath, 0.025 mm accuracy, 10,000 points/s	Hymarc Ltd., (613) 727-1584, info@hymarc.com
Range-Imaging (line scan)	TriCam	Active triangulation laser	120 mm depth of field, 60 mm swath, 0.05 mm accuracy	Perceptron Inc., (810) 478-7710, inquiry@perceptron.com
Range-Imaging (line scan)	ALTM 1020	TOF laser time-interval	330-1000 m range, 15 cm accuracy, 20° swath	Optech Inc., (416) 661-5904
Range-Imaging (area scan)	Rangecam 7000	Laser or strobe triangulation	uses standard CCD camera and light plane projector	Range Vision Inc. (604) 473-9411
Range-Imaging (area scan)	LASAR	TOF, AM Lidar	2–40 m range, 60 × 70° max field of view, 360,000 samples/s	Perceptron Inc., (810) 478-7710
Position Tracking	OPTOTRAK	Active target triangulation	up to 255 targets, submillimeter accuracy, 5000 3 DoF samples/s	Northern Digital Inc., (519) 884-5142
Position Tracking	Flock of Birds	Magnetic field based	up to 30 position/orientation targets, approx. 10 mm acuracy, 144 6-DoF samples/s	Ascension Technology Corp. (802) 860-6440

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