NONCONTACT RANGING SYSTEMS FOR MOBILE ROBOTS

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Recent years have brought about a tremendous rise in the envisioned potential of robotic systems, and correspondingly a significant increase in the number of proposed applications involving mobility. These on-their-own robots have been employed in the factory as automatic guided vehicles (AGVs), transporting workpieces from one workstation to another. In the warehouse, automated storage and retrieval systems are filing parts away, remembering their locations, and keeping a running inventory. The military has been exploring potential uses of mobile robots for fighting fires, handling ammunition, and conducting underwater search and inspection operations, among others.

The problems associated with sending a robot into such unstructured environments call for such special considerations in sensor selection as:

- Field of view
- Range capability
- Ability to detect a variety of objects in the environment
- Real-time operation
- Concise, easy-to-read data
- Redundancy
- Simplicity
- Power consumption
- Size

We will briefly examine the current noncontact distance measurement techniques in conjunction with the acoustic, optic, and electromagnetic regions of the energy spectrum in which they operate.

PROXIMITY

Proximity sensors extend the sensing range of direct-contact tactile or haptic sensors out to a fraction of an inch to a few feet. They generally provide only limited range information (i.e., presence or absence of an object), and can be classified according to specific properties used to initiate a switching action.

Permanent-magnet. This type of sensor is good at sensing ferrous metal objects over very short distances, but is inappropriate on a mobile robotic platform for general object detection.

Induction. Inductive sensors have limited use on mobile robots for object detection, except for very application-specific instances.

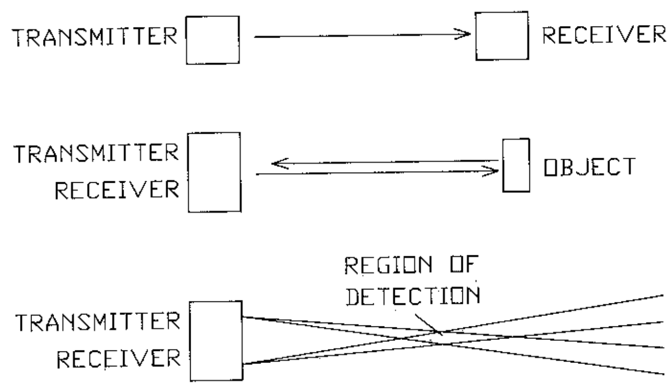


Figure 1. *Optical proximity sensors can be broken into three categories: a) break-beam, b) reflective, and c) diffuse. Figure 1c is a special case of the diffuse type: the convergent proximity sensor.*

Ultrasonic. These sensors are useful over longer distances for detecting most objects.

Optical. This category can be broken down into three subcategories: *break-beam*, *reflective*, and *diffuse*. The break-beam is self-explanatory; the reflective type is an evolution of the break-beam which uses a mirror to colocate the transmitter and receiver. Also shown in Figure 1 is a special configuration of the diffuse category, the convergent optical proximity sensor, which decouples any dependence on the reflectivity of the target surface, very helpful where targets are not well-displaced from background surfaces.

Capacitive. These are effective only for short-range detection, and therefore seldom used on mobile robotic systems.

TRIANGULATION

The ancient ranging technique of triangulation is based on a simple trigonometric method for calculating the distances and angles needed to determine object location: the Law of Sines. The length of one side, b, can be determined as a function of another side, a, and the angles, B and A, opposite those sides, as:

$$b = a \frac{\sin B}{\sin A}$$

Triangulation ranging systems can be classified as *passive* or

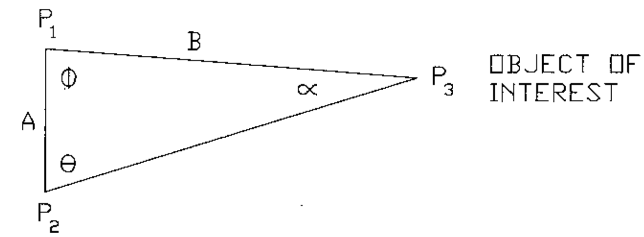


Figure 2. *In practical applications of triangulation ranging, B would be the range (distance) to the desired object. Observed angles at P1 and P2 can be used in conjunction with known separation A to calculate the range to P3.*

active. Passive systems use only ambient scene lighting, whereas active systems employ a controlled light source, such as a laser, directed at the observed point. In either case, an array of range points can be determined by adjusting the incident angles of the detectors and/or the light source in a raster sequence. The resulting range map is a 3-D image of the environment in front of the sensor. The limitations of passive systems are that they require special lighting conditions if the environment is too dark; they also suffer from a correspondence problem arising from the difficulty in matching points seen by one sensor with those seen by the other. Active triangulation systems are free of these problems, but they do encounter instances of no recorded strike because of specular reflectance or surface absorption of the light.

Limiting factors common to all triangulation sensors include angular measurement inaccuracies and a "missing parts" problem, where only certain parts of a scene can be observed from any one viewing location. The offset distance between the viewing locations, which can cause occlusion of the target, necessitates a system design that includes a tradeoff—as the baseline measurement increases, the range accuracy increases but problems due to directional occlusion worsen.

Stereo Disparity. When an object is viewed from two locations on a plane normal to the direction of vision, the image as seen from one position will shift laterally when viewed from the other. This displacement, known as disparity, is inversely proportional to the distance of the object. A ranging system using stereopsis requires two cameras or a single camera that can move laterally. A point in the image of one camera must be identified, and then located in the image of the other camera, which can sometimes be very difficult. The positions of both points must be measured with respect to a common reference, and the distance calculated, a computationally expensive procedure.

Active Triangulation. In place of one of the cameras, a laser

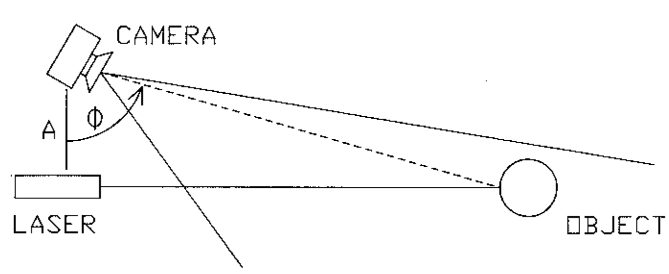


Figure 3. *Active or laser triangulation uses a laser or an LED light source instead of ambient light to illuminate the target. The measured angle Φ decreases as the object moves closer to the laser source.*

(or LED) light source is aimed at the object's surface. The remaining camera is offset from this source by a known distance and configured so as to hold the illuminated spot within its field of view (see Figure 3). From this image the range to the surface can be determined, using the Law of Sines.

Structured Light. An active light source projects a pattern of light (either a line, a series of spots, or a grid pattern) onto the object's surface, and the camera observes the pattern from its offset vantage point. Range is determined by triangulation and manifests itself in the distortions caused in the pattern by variations in the depth of the scene. The use of these special lighting effects tends to reduce the computational complexity and improve the reliability of 3-D object analysis.

Known Target Size. Range is again calculated through simple trigonometry. The known baseline, instead of being between two cameras (or a detector and a light source) on the robot, is now the target itself (see Figure 4). The only limiting constraint (besides knowing the size of the target) is that the target must be normal to the optical axis of the sensor, which, in the case of a passive system, can be an ordinary CCD camera. The standard lens equation applies.

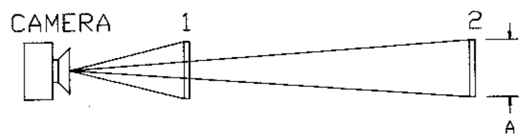


Figure 4. *The angle subtended by an object of known dimension is observed to increase as distance decreases in moving from position 2 to position 1. This fact can be used to calculate the unknown range.*

TIME OF FLIGHT

Time-of-flight (TOF) systems measure the time between an energy pulse emission (typically ultrasonic, radio, or light source) and the return of the echo resulting from its reflectance off an object. Distance is determined by multiplying the velocity of the energy wave by one-half the time required to travel the round-trip distance. The advantages of such systems arise from the direct nature of their active sensing. Transmissions are straight-line from transducer to object, and the returned signal follows essentially the same direct path back to the receiver. It is possible for the transmitting and receiving transducers to be the same device. The absolute range to an observed point is directly available as output that requires no complicated analysis, and the technique is not based on any assumptions about the target's planar characteristics. Limitations are primarily related to the properties of the emitted energy, which vary across the spectrum.

PHASE MODULATION

An unbroken beam of modulated energy (laser or radar) is directed toward the target. A portion of this wave is reflected by the object and returned to the detector along a direct path. This returned energy is compared to a simultaneously generated reference beam that has been split off from the original signal, and the relative phase shift between the two is measured. This phase shift is a function of the round-trip distance the wave has traveled. Accuracies approach those achievable by pulsed TOF methods. Even greater measurement accuracy and overall range can be achieved when cooperative targets, such as retroreflectors, are attached to the targets.

FREQUENCY MODULATION

FM radar involves the transmission of a continuous electromagnetic wave, modulated by a periodic triangular signal that varies the carrier frequency linearly above and below the mean frequency (see Figure 5). The transmitter thus emits a signal that varies in frequency as a linear function of time. The signal reflected off the target is compared with a reference signal taken directly from the transmitter. The received frequency curve will be displaced along the time axis relative to the reference frequency curve by an amount equal to the time required for wave propagation to the target and back. Advances in wavelength control of laser diodes now permit this radar ranging technique to be used with lasers, since the frequency or wavelength of a laser diode can be shifted by varying its temperature. FM has an advantage over phase modulation in that a single distance measurement is not ambiguous. However, several disadvantages are associated with the requirements of coherence of a laser beam and the linearity and repeatability of the frequency ramp.

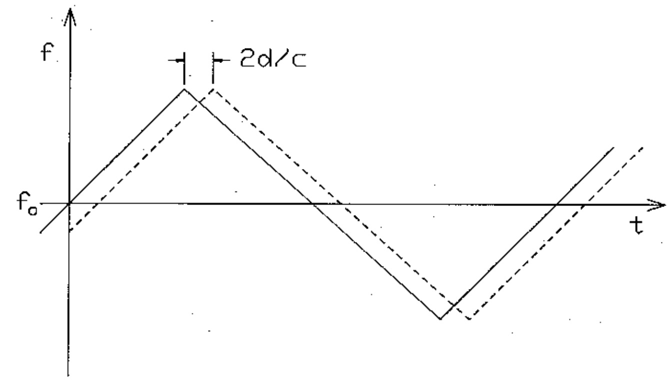


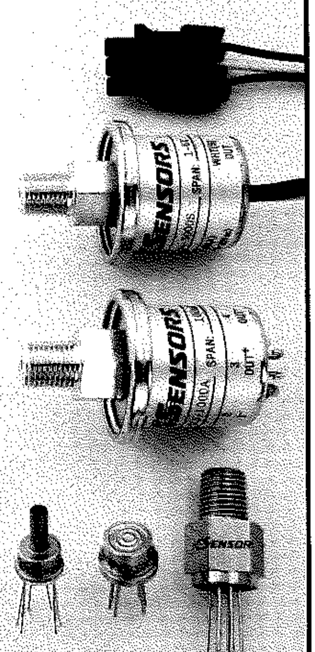
Figure 5. *In frequency modulation systems, the reflected signal (dashed line) is displaced along the time axis by an amount proportional to the target range. $T = 2d/c$ (T = round-trip propagation time, d = distance to target, c = speed of light)*

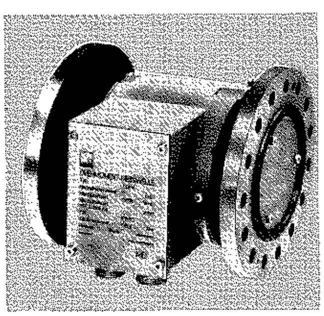
INTERFEROMETRY

This ranging method is based on the interference patterns that occur when two energy waves caused to travel different paths are compared. The most common energy source is coherent laser light. If the length of one of the optical paths is changed, the two beams will interact in such a way that clearly visible constructive and destructive interference fringes are produced. Typical systems consist of a laser emitter, a series of beamsplitters and directional mirrors, and a fringe counter (see Figure 6). Important constraints on using this technique include:

- Only relative distance measurements are possible
- Measurements are cumulative and therefore require continuous line-of-sight contact between target and system
- Measured distances lie along straight-line paths
- Retroreflectors must be installed on each target
- Environmental factors such as air turbulence and temperature changes can also cause problems

The use of interferometers in robotic applications was initially





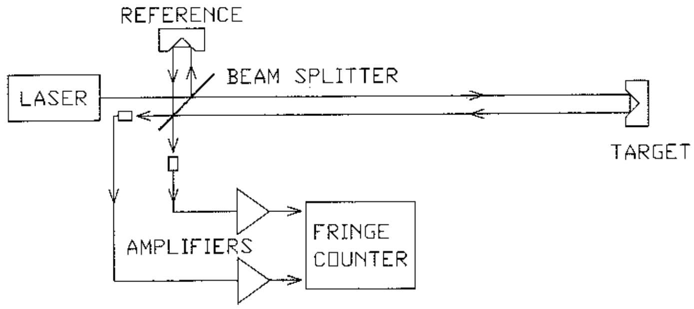


Figure 6. *Interferometer block diagram. A retroreflector must be placed on the target of interest.*

limited to measurement of single-axis linear motion, but recent developments have expanded their applicability to 3-D six-degree-of-freedom systems. These are known as "tracking" interferometers because the returning beam is also used by the system to track the lateral motion of retroreflective mirrors mounted on the object. Robotic tracking systems currently in existence are capable of precision tracking of manipulators performing nonrectilinear motions in six degrees of freedom.

SWEPT FOCUS

The swept-focus technique uses a modified video camera with a single lens of very short depth of field to produce an image in which only a narrow interval of range in object space is in focus at any given time. To perform ranging, the lens is successively positioned at hundreds of discrete, precalculated positions, reading and storing the integrated high-frequency data as it becomes available at each position before moving to the next. At the end of this process, the profile of high-frequency response with range is processed to reduce noise effects, and then analyzed to determine the locations of all significant peaks. Each peak represents the best-focus location of a target. The distance to each target can be found by reading from a look-up table the object range corresponding to the lens position where the peak occurred. The speed of this type of sensor is currently limited by the standard video frame rate of 60 Hz. Ranging accuracy and separation of closely spaced targets are limited by the physical constraints of the lens. However, the system has acceptable accuracy for most applications, will locate multiple targets at different ranges, is not computation intensive, does not suffer from the "missing parts" problem, and operates passively in ambient light.

RETURN-SIGNAL INTENSITY

Return-signal intensity systems are based on the inverse square law for emitted energy that states that as the distance from a point source increases, the intensity of the source diminishes as a function of the square of the distance. If the target surface were Lambertian (ideally reflective scattering energy with equal probability in all directions), a computationally simple range calculation would be possible. However, changes in reflectivity due to surface topography preclude return-signal intensity from being a reliable indicator of distance under most conditions.

Researchers at the MIT AI lab are experimenting with this concept, using a pair of identical point source LEDs positioned a known distance apart, with their incident light focused on the

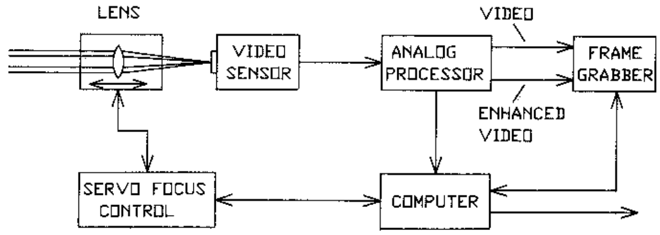


Figure 7. *Block diagram of a passive swept-focus ranging system. (Courtesy Associates and Ferren Corporation, Wainscott, NY)*

target surface. The emitters are individually fired, and the returned energy from each is measured sequentially by a photodetector. If the power of both sources were the same, the intensity of the return signal as sensed by the receiver should also be the same, if the sources were colocated. In this case, however, one of the emitters is closer to the scene, producing a difference in the return signal intensity produced by the two sources. This measurable difference can be exploited to yield absolute range values.

APPLICABLE TECHNOLOGIES

Acoustical. Acoustical ranging can be implemented using triangulation, time of flight, phase shift measurement, or a combination of these techniques. The direction and velocity of a moving object can also be determined by measuring the Doppler shift. Typically, triangulation and time-of-flight methods transmit sound energy in pulses and are effective at longer distances for navigation and positioning, and at shorter distances for object detection. Phase shift, which involves the transmission of a continuous sound wave, is better suited for situations where a single, dominant target is present.

The performance of acoustical ranging systems is significantly affected by both sensor design characteristics and a number of environmental phenomena, including:

- Attenuation of sound energy over distance
- Absorption of energy by humidity and dust in the air and at the reflecting surface
- Air temperature, which affects the velocity of sound
- Emitted power and frequency of operation
- Beam dispersion angle of the transducer

Nevertheless, ultrasonic sensors are a powerful and practical method of range determination for selected applications. Simple construction of the transducers makes them reliable and economical. The low cost factor also makes design redundancy feasible, further improving system reliability and effectiveness.

Optical. Most active, optically-based distance measuring devices use laser sources, and are generally considered the quickest and most accurate way to obtain range information. Lasers can be found in ranging systems based on triangulation, time of flight, phase modulation, interferometry, and return-signal intensity. Advantages of such laser-based systems arise from the inherent characteristics of the laser light itself—brightness and intensity, narrow and collimated beams, and single-wavelength light. Disadvantages include the potential eye hazard of certain lasers, the high-voltage power supplies required by gas lasers, the need for a highly accurate beam delivery system, and the wide dynamic range of the returning energy (between

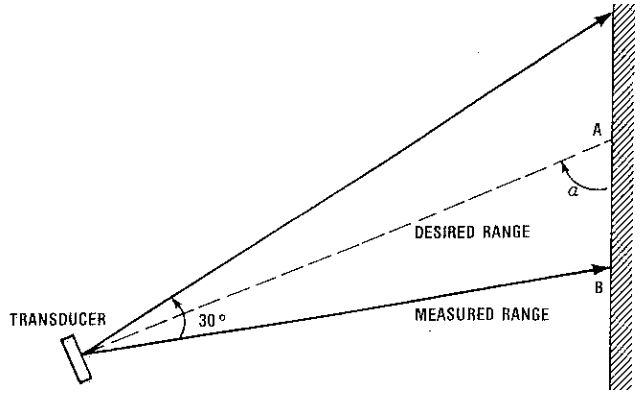


Figure 8. *Best results are obtained where the beam centerline is maintained normal to the target surface. For a 30 degree beam dispersion angle at a distance of 15 feet from a flat target, with an angle of incidence, α, of 70 degrees, the theoretical error could be as much as 10 inches.*

80 and 100 dB), which complicates detector electronics design. Lasing materials are frequently unstable and have short lifetimes. Finally, some laser-based ranging techniques require the use of retroreflective mirrors or prisms at observed points, effectively eliminating selective sensing.

For use with mobile robotic systems, optical ranging must be able to function well under normal ambient lighting conditions. Some systems use an incandescent source that is directed through a slit or patterned mask and projected onto the surface. Others use laser beams that are mechanically or electronically scanned at high rates. The most important consideration is to select a light source whose intensity peaks at a spectral frequency other than that of the ambient light. The camera should be equipped with a matching narrow band filter to complement the source and improve detection. Ambient light effects can also be reduced by modulating the source signal over time, then demodulating the received energy at the camera end.

Electromagnetic. Radar systems, when combined with computerized signal processing, can produce astonishing accuracies in target discrimination and range computation. They are also effective for measuring the speed of moving objects by Doppler shift methods. Ranging is accomplished by pulsed time-of-flight methods or continuous wave phase or frequency modulation. Pulsed energy is preferable for long-distance detection, while continuous wave emission works better at shorter ranges. Of particular importance in radar ranging is the configuration of the transmitting and receiving antenna. Systems employing a single antenna typically feature a large, concave reflector with the detector positioned at the focal point of the dish. The principal advantage of this single unit arrangement is that the antenna will collect all the returned energy that falls upon it from a beam that is inversely proportional to the diameter of the reflector. The disadvantages include the need to manipulate a large diameter antenna system when narrow beams are transmitted, and the effect of vibration and wind that can necessitate a massive structure. An alternative configuration is a phased array antenna that assembles into an array multiple small antennae separated by distances of a few wavelengths.

Microwave energy is ideally suited for long-range military sensing because the resolution is sufficient, atmospheric attenuation of the beams is minimal, and low-mode guiding structures can be constructed. The relatively long wavelengths provide radar systems with an all-weather capability because they overcome the absorption and scattering effects of the air, weather, and other obscurants. However, they are susceptible to specular reflections at the target surface, necessitating receivers and signal processors with wide dynamic ranges. Shorter wavelengths can be used to produce systems with high angular resolution and small-aperture antennae. (High angular resolution is possible at longer wavelengths, but the antenna size becomes very large.) Therefore, conventional radar systems operating in the microwave portion of the energy spectrum have little applicability to the high-resolution collision avoidance needs of a mobile robotic platform.

The rapidly evolving millimeter wave technology involves that portion of the electromagnetic energy spectrum from wavelengths of about 500 μm to 1 cm. Millimeter waves possess several properties that differ substantially from microwave radiation. For one, the shorter wavelengths produce a narrow beamwidth radar, with relatively small antenna apertures for a given bandwidth. Reduced scattering of the reflected signal by detected objects allows more information to be obtained about the nature of the target than is permitted by longer wavelengths. While the overall physical size of the system is reduced, the smaller apertures mean less collected energy, limiting the effective range of the system. Also, millimeter waves possess an extremely wide frequency range bandwidth, which translates into greater resolution and sensitivity, reduced interference between mutual users of the band, and improved security because of the large space in which to hide.

Compared to microwaves, millimeter waves display greater interaction with the environment. The resultant atmospheric attenuation limits the range and prevents operation of such devices in all-weather conditions. Likely applications of this technology include remote environmental sensing, interference-free communications and radar, low-angle tracking radar, high resolution and imaging radar, spectroscopy, and mobile platform collision avoidance.

Although there are at present no commercial sources of practical millimeter wave ranging devices, several contractors are involved in supplying such equipment to the military. While development costs might run as high as $1 million, with lead times approaching a year or more, the indication is that individual transmitter, receiver, and antenna units may eventually cost as little as $100 apiece, and fit into packages as small as an eight-inch cube.

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