Location Sensing Techniques*

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Triangulation, scene analysis, and proximity are the three principal techniques for automatic location sensing. Location systems may employ them individually or in combination. For each technique we describe its basic concepts, list some implementation technologies, and give examples of location systems which use the technique.

1 Triangulation

The triangulation location sensing technique uses the geometric properties of triangles to compute object locations. Triangulation is divisible into the subcategories of *lateration*, using distance measurements, and *angulation*, using primarily angle or bearing measurements.

1.1 Lateration

We define the term lateration to mean for distance measurements what angulation means for angles. Lateration computes the position of an object by measuring its distance from multiple reference positions. Calculating an object's position in two dimensions requires distance measurements from 3 non-collinear points as shown in Figure 1. In 3 dimensions, distance measurements from 4 non-coplanar points are required. Domain-specific knowledge may reduce the number of required distance measurements. For example, the Active Bat Location System measures distance from indoor mobile tags, called Bats, to a grid of ceiling mounted ultrasound sensors [4]. A Bat's 3-dimensional position can be determined using only 3 distance measurements because the sensors in the ceiling are always above the receiver. The geometric ambiguity of only 3 distance measurements can be resolved because the Bat is known to be below the sensors and not in the alternate possible position on the next floor or roof above the sensor grid.

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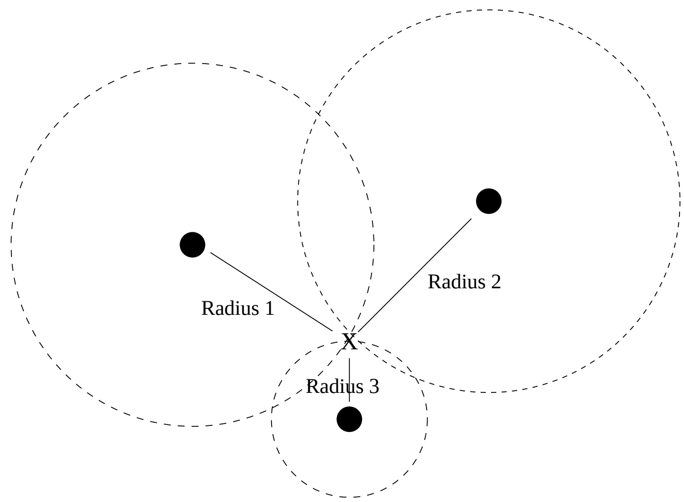

Figure 1: Determining 2D position using lateration requires distance measurements between the object 'X' and 3 non-collinear points.

There are three general approaches to measuring the distances required by the lateration technique.

1. **Direct.** Direct measurement of distance uses a physical action or movement. For example, a robot can extend a probe until it touches something solid or take measurements with a tape measure. Direct distance measurements are simple to understand but difficult to obtain automatically due to the complexities involved in coordinating autonomous physical movement.

2. **Time-of-Flight.** Measuring distance from an object to some point P using time-of-flight means measuring the time it takes to travel between the object and point P at a known velocity. The object itself may be moving, such as an airplane traveling at a known velocity for a given time interval, or, as is far more typical, the object is approximately stationary and we are instead observing the difference in transmission and arrival time of an emitted signal. For example, sound waves have a velocity of approximately 344 meters per second in 21°C air. Therefore, an ultrasound pulse sent by an object and arriving at point P 14.5 milliseconds later allows us to conclude that the object is 5 meters away from point P. Measuring the time-of-flight of light or radio is also possible but requires clocks with much higher resolution (by six orders of magnitude) then those used for timing ultrasound since a light pulse emitted by the object has a velocity of 299,792,458 meters per second and will travel the 5 meters to point P in 16.7 nanoseconds. Also, depending on the capabilities of the object and the receiver at point P, it may be necessary to measure a round-trip delay corresponding to twice the distance.

Ignoring pulses arriving at point P via an indirect (and hence longer) path caused by reflections in the environment is a challenge in measuring time-of-flight since direct and reflected pulses look identical. Active Bats and others statistically prune away reflected measurements by aggregating multiple receivers' measurements and observing the environment's reflective properties.

Another issue in taking time-of-flight measurements is agreement about the time. When only one measurement is needed, as with round-trip sound or radar reflections, "agreement" is simple because the transmitting object is also the receiver and must simply maintain its own time with sufficient precision to compute the distance. However, in a system like GPS, the receiver is not synchronized with the satellite transmitters and thus cannot precisely measure the time it took the signal to reach the ground from space. Therefore, GPS satellites are precisely synchronized with each other and transmit their local time in the signal allowing receivers to compute the *difference* in time-of-flight. GPS receivers can compute their 3-dimensional position (latitude, longitude, and elevation) using 4 satellites. The satellites are always above the receivers so only 3 satellites would normally be required to provide distance measurements in order to estimate a 3D position. However in GPS a fourth satellite measurement is required to allow us to solve for the forth unknown, the error between the receiver clock and the synchronized satellite clocks – a system of four equations (4 satellite signals) and four unknowns (X, Y, Z, and transmission time). Refer to [3] for an excellent summary of GPS theory. To maintain synchronization, each of the 27 GPS satellites contains four cesium/rubidium atomic clocks which are locally averaged to maintain a time accuracy of 1 part in 10^{13} seconds. Furthermore, each satellite gets synchronized daily to the more accurate atomic clocks at US Naval Observatory by US Air Force GPS ground control.

Time-of-flight location sensing systems include GPS, the Active Bat Location System [4], the Cricket Location Support System [10], Bluesoft [8], and PulsON Time Modulated Ultra Wideband technology [12].

3. **Attenuation.** The intensity of an emitted signal decreases as the distance from the emission source increases. The decrease relative to the original intensity is the attenuation. Given a function correlating attenuation and distance for a type of emission and the original strength of the emission, it is possible to estimate the distance from an object to some point P by measuring the strength of the emission when it reaches P. For example, a free space radio signal emitted by an object will be attenuated by a factor proportional to $1/r^2$ when it reaches point P at distance r from the object.

   In environments with many obstructions such as an indoor office space, measuring distance using attenuation is usually less accurate than time-of-flight. Signal propagation issues such as reflection, refraction, and mul-

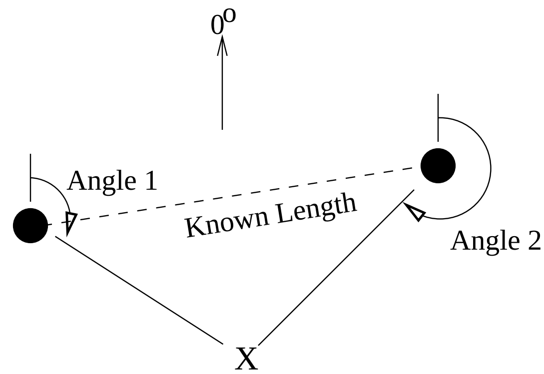

Figure 2: This example of 2D angulation illustrates locating object 'X' using angles relative to a 0° reference vector and the distance between two reference points. 2D angulation always requires at least two angle and one distance measurement to unambiguously locate an object.

tipath cause the attenuation to correlate poorly with distance resulting in inaccurate and imprecise distance estimates.

The SpotON ad hoc location system implements attenuation measurement using low-cost tags. SpotON tags use radio signal attenuation to estimate inter-tag distance [5] and exploits the density of tag clusters and correlation of multiple measurements to mitigate some of the signal propagation difficulties.

1.2 Angulation

Angulation is similar to lateration except, instead of distances, angles are used for determining the position of an object. In general, two dimensional angulation requires two angle measurements and one length measurement such as the distance between the reference points as shown in Figure 2. In three dimensions, one length measurement, one azimuth measurement, and two angle measurements are needed to specify a precise position. Angulation implementations sometimes choose to designate a constant reference vector (e.g. magnetic north) as 0°.

Phased antenna arrays are an excellent enabling technology for the angulation technique. Multiple antennas with known separation measure the time of arrival of a signal. Given the differences in arrival times and the geometry of the receiving array, it is then possible to compute the angle from which the emission originated. If there are enough elements in the array and large enough separations, the angulation calculation can be performed.

The VHF Omnidirectional Ranging (VOR) aircraft navigation system is a different example of the angulation technique. As any pilot knows, VOR stations are ground-based transmitters in known locations which repeatedly broadcast

Figure 3: Horizon shapes extracted from a visual scene can be used statically to look up the observer's location from a prebuilt dataset or dynamically to compute movement of the vehicle mounted camera.

2 simultaneous signal pulses. The first signal is an omnidirectional reference containing the station's identity. The second signal is swept rapidly through 360° like the light from a lighthouse at a rate such that the signals are in phase at magnetic north and 180° out of phase to the south. By measuring the phase shift, aircraft listening to a VOR station can compute their "radial," the compass angle formed by the direct vector to the VOR station and magnetic north, to 1°. Aircraft location can be computed via angulation using 2 VOR stations. VHF radio signals are limited to line-of-sight reception and the range of the transmitted signals is 40-130 nautical miles.

2 Scene Analysis

The scene analysis location sensing technique uses features of a scene observed from a particular vantage point to draw conclusions about the location of the observer or of objects in the scene. Usually the observed scenes are simplified to obtain features that are easy to represent and compare (e.g., the shape of horizon silhouettes such as Figure 3 as seen by a vehicle mounted camera [2]). In *static* scene analysis, observed features are looked up in a predefined dataset that maps them to object locations. In contrast, *differential* scene analysis tracks the difference between successive scenes to estimate location. Differences in the scenes will correspond to movements of the observer and if features in the scenes are known to be at specific positions, the observer can compute its own position relative to them.

The advantage of scene analysis is that the location of objects can be inferred using passive observation and features that do not correspond to geometric angles or distances As we have seen, measuring geometric quantities often requires motion or the emission of signals, both of which can compromise privacy and can require more power. The disadvantage of scene analysis is that the observer needs to have access to the features of the environment against which it will compare its observed scenes. Furthermore, changes to the environment in a way that alters the perceived features of the scenes may necessitate reconstruction of the predefined dataset or retrieval of an entirely new dataset.

The scene itself can consist of visual images, such as frames captured by a wearable camera [11], or any other measurable physical phenomena, such as the electromagnetic characteristics that occur when an object is at a particular position and orientation. The Microsoft Research RADAR location system is an example of the latter. RADAR uses a dataset of signal strength measurements created by observing the radio transmissions of an 802.11 wireless networking device at many positions and orientations throughout a building [1]. The location of other 802.11 network devices can then be computed by performing table lookup on the prebuilt dataset. The observed features, signal strength values in this case, correlate with particular locations in the building but do not directly map to geometric lengths and angles describing those locations.

3 Proximity

A proximity location sensing technique entails determining when an object is "near" a known location. The object's presence is sensed using a physical phenomenon with limited range. There are three general approaches to sensing proximity:

1. **Detecting physical contact.** Detecting physical contact with an object is the most basic sort of proximity sensing. Technologies for sensing physical contact include pressure sensors, touch sensors, and capacitive field detectors. Capacitive field detection has been used to implement a Touch Mouse [7] and Contact, a system for intra-body data communication among objects in direct contact with a person's skin [9].

2. **Monitoring wireless cellular access points.** Monitoring when a mobile device is in range of one or more access points in a wireless cellular network is another implementation of the proximity location technique and is illustrated by Figure 4. Examples of such systems include the Active Badge Location System [13] and the Xerox ParcTAB System [15], both using diffuse infrared cells in an office environment, and the Carnegie Mellon Wireless Andrew [6] using a campus-wide 802.11 wireless radio network.

3. **Observing automatic ID systems.** A third implementation of the proximity location sensing technique uses automatic identification systems such as credit card point-of-sale terminals, computer login histories, land-line telephone records, electronic card lock logs, and identification tags such as electronic highway E-Toll systems, UPC product codes, and injectable livestock identification capsules [14]. If the device scanning the

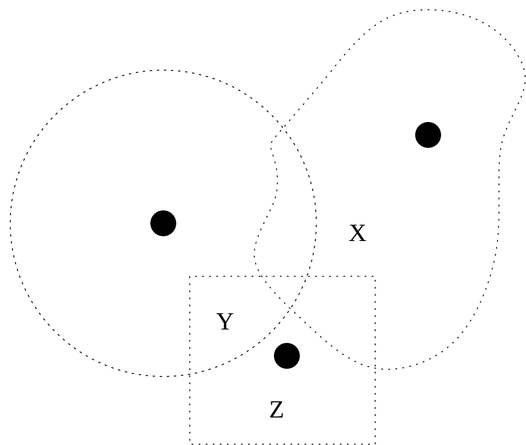

Figure 4: Objects 'X', 'Y', and 'Z' are located by monitoring their connectivity to one or more access point in a wireless cellular network. The cell geometry is an artifact of the wireless technology technology used in the implementation. For example, a radio cellular network cell may have the shape of the region containing object 'X' while diffuse infrared in a room is constrained by the walls resulting in a square shape.

label, interrogating the tag, or monitoring the transaction has a known location, the location of the mobile object can be inferred.

Proximity approaches may need to be combined with identification systems if they do not include a method for identification in the proximity detection. For example, the Contact system [9] enables communication between objects a user is touching and all these objects can exchange identification information over the same communication channel. Livestock tags have unique signatures identifying individual animals. Similarly for cell phones. In contrast, the Touch Mouse and pressure sensors, require an auxiliary identification system since the method used to detect proximity does not provide identification directly.

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