CHAPTER 7

Location in Ubiquitous Computing

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CONTENTS

7.1 INTRODUCTION

This chapter discusses the fundamentals of location technologies and gives an overview of both historical and current location systems. Location technologies have been an important part of ubiquitous computing (ubicomp) and have been an active topic of research for the past decade. The ability to determine a user's location enables a variety of ubicomp applications that provide services and functionality appropriate to the specific location and context. In other words, location-aware applications use the location of the target to add value to the services they provide. For example, some of the earlier location-aware applications were routing phone calls to the phone closest to the user's current location (Want et al., 1992), sending printouts to the nearest printer, and displaying files and programs specific to the user's location (Schilit et al., 1999). Since the early days, location-aware applications have grown in sophistication and utility, and people rely more and more on these applications. Today, people use location-aware applications in almost any life domain, including entertainment, navigation, asset tracking, health care monitoring, and emergency response. The number of location-aware applications is still growing fast, with the annual market for global positioning system (GPS) and navigation services and products alone projected to grow to U.S.$200 billion by 2015 (Rizos et al., 2005).

Location is one of the most important components of user context (Schilit et al., 1999). In addition to being useful in its own right, location information can also be used to infer additional pieces of context, such as user activity, mode of transportation, and social relationship. For example, spending time at a gym is indicative of exercising, changing location at a speed of 65 miles/h is indicative of driving, and driving someone every morning to and from work is indicative of a close relationship. We refer the reader to Chapter 8 for an in-depth discussion on the use of contextual information in ubicomp.

Location information can be conveyed in absolute, relative, or symbolic form. An absolute location describes an exact position, such as an address or geographic coordinates. For example, AT&T Labs is located at 180 Park Avenue, Florham Park, NJ. A relative location describes a position of an object relative to another absolute location. For instance, Dunn Gardens are located approximately 10 miles north of downtown Seattle, WA. A symbolic location is a descriptive name of a place, such as "home," "work," or "bedroom."

Despite the importance of location information, there is no single location technology that is accurate, low-cost, easy to deploy, and ubiquitous. Instead, there is a collection of location technologies each of which is best suited for a particular situation and need, ranging from accuracy of 1 mm using magnetic fields (Ascension Technology) to tens of kilometers using FM radio signals (Krumm et al., 2003). Since location technologies generally trade off accuracy for coverage and cost, one should choose the location system that satisfies the accuracy requirement of the particular location-aware application of interest. For example, printing a document on the nearest printer will, in most cases, work as well with 1 m accuracy as it will with 1 mm accuracy. This chapter covers a variety of location systems with different accuracy, coverage, and cost trade-offs. In addition, most location-aware applications make an implicit assumption that location of a device, such as a mobile phone, is a good proxy for the location of the human using the device. Although, in practice, it is not always the case (Patel et al., 2006a), for the ease of presentation, this chapter refers to the location of the device and the location of the user using the device interchangeably.

The outline of the rest of the chapter is as follows. Section 7.2 discusses various aspects of location technologies, including ways to specify location, differences between client-based and network-based location systems, common approaches for determining location, and ways to describe location error. Section 7.3 gives an overview of both historical and current location systems, while helping distill why certain design decisions where made for each system. Section 7.4 concludes the chapter and lists some of the remaining challenges in the field of location tracking.

Note that this chapter does not cover the important topics of location modeling, issues related to location privacy, and more advanced stochastic methods for inferring location. See Chapter 3 for a discussion on privacy and Chapter 9 for a description of how to process sequential sensor data.

7.2 CHARACTERIZING LOCATION TECHNOLOGIES

Location technology is a combination of methods and techniques for determining a physical location of an object or a person in the real world. This section describes various aspects of location technologies. The section starts with discussing ways to represent absolute, relative, and symbolic locations. Next, Section 7.2.2 describes the differences between client-based, network-based, and network-assisted location systems. Section 7.2.3 surveys popular technologies for location determination. Finally, Section 7.2.4 discusses common sources of location error and ways to report the accuracy of a location system.

7.2.1 Location Representation

Location is a position in a physical space and it can be represented in absolute, relative, or symbolic form. The most common means of specifying a precise absolute location is using the point's degrees of latitude and longitude on the surface of the Earth, as defined by the geographic coordinate system. If Earth were a perfect ellipsoid, the latitude would measure the angle between the point and the equatorial plane from the center of Earth. In reality, however, the latitude, or the geodetic latitude, measures the angle between the equator and a line that is normal to the reference ellipsoid, which approximates the shape of Earth. The longitude measures the angle along the Equator to the point. A line that passes near the Royal Observatory, Greenwich, England, is accepted as the zero-longitude point and it is called a prime meridian. Lines of constant latitude are called parallels and lines of constant longitude are called meridians. Meridians, unlike parallels, are not parallel and all intersect at the north and south poles. This form of representation is often used in outdoor location systems such as GPS. See Figure 7.1 for an example.

One can specify any location on the surface of the Earth using latitude and longitude. For example, Seattle, WA, has latitude of 47.60°N and longitude of 122.33°W. Thus, a vector from the center of the Earth to a point 47.60° north of equator and 122.33° west of Greenwich, England, will pass through Seattle. By adding a vertical distance from the center of the Earth or, more commonly, from the mean sea level at a given point, it is possible to specify any location below or above the surface of the Earth.

Although geographic coordinates are useful for specifying a precise absolute location, they are not convenient to use in the types of applications that involve reasoning with location information by humans. One

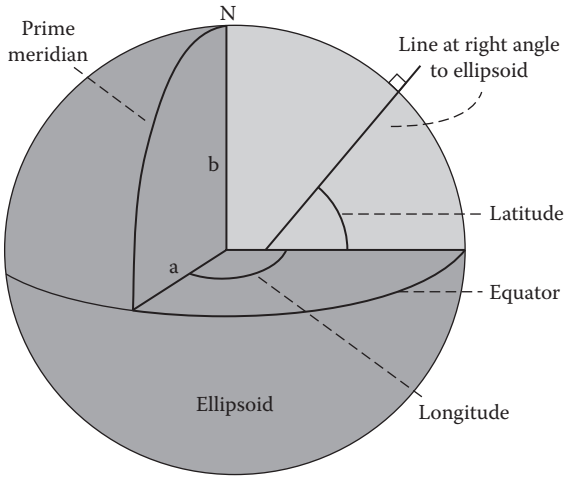

FIGURE 7.1 An example of a latitude and longitude angles to a point on Earth. (Accessed from http://home.online.no/~sigurdhu/artimages/Lat-Long.gif.)

can rarely overhear a person saying: "I am at 47.60 North, 122.33 West. Do you want to grab a coffee at 47.60 North, 122.33 West in half an hour?" As an alternative, it is typical to use an address to specify a location (e.g., 40 St. George Street), a symbolic name of a place that is familiar to both parties (e.g., the mall) or a relative coordinate (e.g., 100 meters north of Main and Ridgedale). A geocoder, such as Microsoft's Virtual Earth or AT&T's Yellow Pages, can be used to translate an address or a zip code into a geographic coordinate. Translating a geographic coordinate into an address or a zip code can be performed using a reverse geocoder.

Describing location within an indoor space is similarly challenging. A system may represent a location using a local coordinate system within the building by specifying an *X* and Y distance from a fixed corner of the building. For a multistory building, an anchor point could be specified for each floor. Although these representations are useful at a system level, they are usually also mapped to higher-level relative or symbolic representations, such as "living room," "bedroom," "Joe's office," or "next to the coffee pot."

7.2.2 Infrastructure and Client-Based Location Systems

This section describes the differences between three classes of location systems: client-based, network-based, and network-assisted. In a client-based

location system, a device computes its own location without relying on the network infrastructure. An example of a client-based location system is GPS, in which a device equipped with a GPS chip calculates its own location using signals received from at least four GPS satellites.

In a network-based location system, the network infrastructure calculates the position of a device. An example of a network-based location system is the Active Badge system (Want et al., 1992), in which a badge carried by the user emits infrared (IR) signals captured by the IR receivers in the ceiling. The receivers, in turn, transmit signal data to a networked processor that computes the badge's location.

In a network-assisted location system, both the device and the infrastructure participate in computing the location of the device. An example of a network-assisted location system is the Assisted GPS, in which a device calculates its own location based on its GPS measurements and additional information about the GPS constellation received over the cellular link from the cellular network infrastructure. The additional information allows the device to calculate its location even if fewer than four satellites are in view and it reduces the time from turning on of the device to the initial location acquisition.

The main advantage of a client-based location system is that it preserves the location privacy of the device. Since the mobile device simply listens to the beacons from the infrastructure without transmitting data, the infrastructure has no way of determining the location of the device, unless the device is willing to share the data. On the other hand, calculating the location on a device may reduce its battery life and it adds requirements on the device's processing and storage capabilities. Note that the network infrastructure may learn the device's location when the device requires additional information or services based on its location. For example, requesting maps or nearby restaurants requires the device to disclose its location with a certain degree of accuracy. For more information about preserving a user's privacy, see Chapter 3.

7.2.3 Approaches to Determining Location

This section describes six fundamental techniques for determining the location of a device: proximity, trilateration, hyperbolic lateration, triangulation, fingerprinting, and dead reckoning. Some of these techniques assume a presence of one or more reference points, whose precise location is known in advance. Examples of a reference point include a GPS satellite, a WiFi access point (AP), or a cellular tower.

7.2.3.1 Proximity

Proximity sensing is the simplest location technique. It uses the closeness of a device to a reference point to estimate the location of the device. The device's location is typically estimated to be the location of the reference point. Either the device or the reference point can sense the proximity. Note that detecting a device in close proximity does not necessarily reveal the identity of the device. Therefore, a separate identity detection mechanism may be necessary for recognizing the identity of the device.

Proximity can be detected through either direct physical contact or detection of the device being in range of one or more reference points. For example, stepping on a pressure sensor reveals the presence of an individual on the sensor and communicating with a WiFi AP indicates that the device is near the AP. In the latter case, proximity sensing relies on a limited range of coverage of the underlying wireless communication technology. For instance, the range of a near-field communication device is a few centimeters, the range of a Bluetooth device is tens of meters, the range of a WiFi device is hundreds of meters and a cellular phone may receive signals kilometers away. If the device happens to be in a range of several reference points, it is possible to compute a more accurate location estimate. For instance, it is possible to estimate the location of the device as an average of reference point positions. If the strength of the signal with which the reference points can overhear the device is available, a more precise location can be obtained using the weighted average of the reference point positions. A more advanced technique that uses the actual distances between a device and reference points is called trilateration, which is discussed in the next section.

7.2.3.2 Trilateration

Trilateration is a location technique that computes the position of a device by measuring the distance between the device and a number of reference points at known locations. The number of reference points required for computing the location is one greater than the number of the physical space dimensions. For example, calculating the device's location in two dimensions (2-D) requires three noncoplanar reference points, whereas calculating the device's location in 3-D requires four reference points.

Figure 7.2 shows an example of trilateration in 2-D. Each black dot represents a reference point and it defines a center of a circle with the radius equal to the estimated distance to the device. Thus, estimating the distance to a single reference point yields an infinite number of possible locations

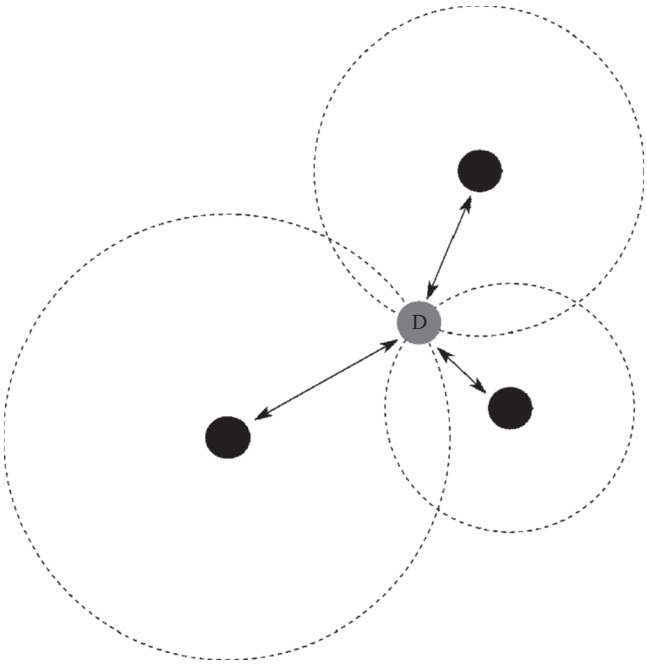

FIGURE 7.2 Example of trilateration in 2-D. The black dots represent reference points. The gray dot represents the location of the device.

of the device on the perimeter of the circle; estimating the distances to two reference points yields two possible locations of the device at the intersections of the two circles; and estimating the distances to three reference points uniquely defines the device's location.

To estimate the distance between a device and a reference point, it is common to either measure the time-of-flight of the signal or to measure the attenuation of the strength of the signal at the receiver. The next two sections cover these distance estimation techniques.

7.2.3.2.1 Time of Flight Estimating the time-of-flight of a signal between a device and a reference point is possible because the speed of sound and the speed of light are known quantities (344 m/s in 21°C air for sound and 299,792,458 m/s for light). Therefore, by measuring the time it takes for the signal to travel the distance between the device and the reference point and multiplying it by the speed of travel, it is possible to estimate the traveled distance. For instance, if an ultrasonic pulse sent from a device to a reference point reached its destination in 29 ms, the distance between

the two is 10 m. A radio or light signal would cover the same distance in 33.4 ns.

Measuring the time-of-flight requires precise clock synchronization between the device and the reference point. This is especially true when estimating the time-of-flight of a radio or light signal because small skews in the clocks will result in large measurement errors. To avoid the clock synchronization problem, instead of measuring the time-of-flight between two devices, some systems measure the round-trip delay and divide it by 2. This eliminates the need to synchronize clocks on two devices because the same device both transmits and receives the signal.

The time-of-flight can be measured either by the device or the network infrastructure. In the former, each reference point transmits a signal that is being received and decoded by the device. In the latter, the device sends a signal that is being received by all reference points. In both cases, the reference points need to have synchronized clocks for the precise time-of-flight calculation.

7.2.3.2.2 Signal Strength Attenuation Another approach to estimate the distance between a device and a reference point is based on the ability to estimate the decrease in the strength of a signal as it travels away from its source. The formula that estimates the strength of the signal at a certain distance from the source is called the signal attenuation model.

A signal attenuation model depends on a multitude of factors, including the distance from the source, terrain contours, physical environment, propagation medium, and the height of the antennas at the source and the destination. For instance, the signal attenuation model for free space far-field radio frequency (RF) states that the strength of a radio signal decreases by a factor of $1/r^2$, where r is the distance from the radio source. For near-field inductively coupled communication, the attenuation of the signal could decrease by a factor of as high as $1/r^6$. Thus, given the correct signal attenuation model and the strengths of the signal at the source and at the destination, it is therefore possible to estimate the distance between the source and the destination.

Unfortunately, in more complex physical environments, such as an indoor office space, radio attenuation models have trouble estimating the distance accurately due to complex interactions of the signal with objects in the physical space. As the signal travels, it may be reflected, refracted, or diffracted, which may cause the signal to change direction, reach areas that would not be possible to reach if the radio signals traveled in a direct

line, or arrive at the destination by two or more paths. These complex interactions present a formidable challenge for creating accurate signal attenuation models.

7.2.3.3 Hyperbolic Lateration

Hyperbolic lateration uses the difference between the signal arrival times from a device to three or more reference points, instead of using the signal travel time itself. The hyperbolic lateration technique is also applicable when a device receives signals that were simultaneously transmitted by three or more reference points. For the ease of presentation, this section explains hyperbolic lateration in 2-D.

The signal transmitted from a device will be received at different times by reference points located at different distances from the device. The difference between the signal arrival times at two reference points restricts the possible location of the device to be along a hyperbolic line, with the two reference points serving as the foci of the hyperbola. In other words, transmitting a signal while being located at any point on the hyperbola will result in the same time difference of arrival of the signal to the two reference points. Adding a third reference point gives two more pairs of TDOA and therefore two more hyperbolas. Intersection of any two of the hyperbolas defines the unique possible location of the device. Figure 7.3 shows an example of hyperbolic lateration in two dimensions. The intersection of the two hyperbolas uniquely defines the location of a device.

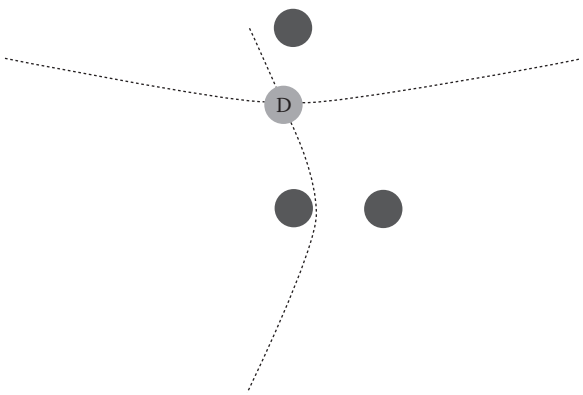

FIGURE 7.3 An example of hyperbolic lateration in 2-D. The black dots represent reference points. The gray dot represents the location of the device.

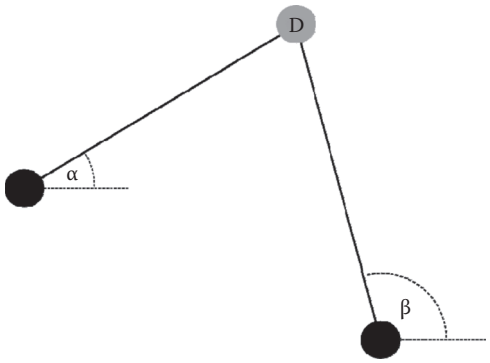

FIGURE 7.4 An example of triangulation in 2-D. The black dots represent reference points. The gray dot represents the location of the device.

7.2.3.4 Triangulation

Triangulation uses the angle of arrival (AOA) of signals traveling from a device to reference points to estimate the device's location. See Figure 7.4 for an example of triangulation in 2-D. Measuring the angle at which the signal arrives from the device (represented as the gray dot) to a reference point (represented as a black dot) restricts the position of the device along the line that passes through the reference point along the AOA. Measuring angles from two reference points results in two lines that uniquely define the device's location at the point of intersection. Thus, it is enough to have angle measurements from only two reference points to determine the location of the device in two dimensions; in practice, however, more than two reference points are used to reduce angle measurement errors.

To estimate the AOA of a signal, either a directional antenna or an antenna array is needed. Since neither is typically available on a mobile device, most existing location systems based on triangulation choose to measure the AOA at the reference points.

7.2.3.5 Fingerprinting

Fingerprinting is a location technology that uses pattern matching techniques to estimate the location of a device. For the ease of presentation, this section describes RF fingerprinting; however, the techniques presented in this section are applicable to other signal sources as well, such as sound and colored light.

RF fingerprinting relies on two properties of radio signals: temporal stability and spatial variability. Temporal stability refers to the stability

of a radio signal from a radio source at any given location over time. For example, the strength of the signal from a nearby cellular tower at one's office is likely to be similar tomorrow and next week. Spatial variability refers to the variability of the radio signal from the same radio source at two different locations. For instance, the strength of the signal from a nearby cellular tower is different at the office and at the cafeteria. Fingerprinting location systems take advantage of these two properties by capturing radio profiles at various physical locations and using them for location determination at a later time.

The accuracy of a fingerprinting system is closely tied to the degree of spatial variability of the signal. For example, signal strength from WiFi APs exhibits spatial variability at the 1 to 10 m level, or, in other words, a given WiFi AP may be heard stronger or not at all a few meters away. This allows for WiFi-based fingerprinting systems with about 1 m of spatial error.

Fingerprinting relies on a training phase to build a radio map of the target environment before it can be used for location determination. During the training phase, a device moves through the environment, taking measurements of the strength of signals emanating from a group of radio sources (e.g., WiFi APs). An example of a radio measurement is shown in Table 7.1. The table shows a list of WiFi APs and the signal strengths as received from each of the APs.

At the end of the training process, the fingerprinting system has a radio profile for a multitude of locations in the target physical space. Since fingerprinting does not model radio propagation, a fairly dense grid of radio measurements needs to be collected to achieve good accuracy. The original fingerprinting system (Bahl and Padmanabhan, 2000), for example, collected measurements of WiFi signal strengths about 1 m apart.

Once the training phase is complete, a device can estimate its location by collecting a measurement and feeding it to the fingerprinting system, which may reside either on the device itself or in the network infrastructure. The fingerprinting system estimates the location of the device based

TABLE 7.1 An Example of a Measurement that Includes Names, MAC Addresses, and Received Signal Strength Indicator Values of Three WiFi Access Points

SSID (Name)	BSSID (MAC Address)	Signal Strength (RSSI)
linksys	00:0F:66:2A:61:00	18
starbucks	00:0F:C8:00:15:13	15
newark wifi	00:06:25:98:7A:0C	23

on the similarity between the current measurement and the measurements recorded during the training phase.

The similarity between measurements can be computed in a variety of ways, but it is common to use the Euclidean distance in signal space. For example, if one WiFi measurement contains signal strengths for N APs $(S_1,\ldots,S_n)$ and another measurement contains signal strengths for the same N sources $(R_1,\ldots,R_n)$, then the Euclidean distance between the two fingerprints will be calculated as:

$$E = \sqrt{(S_1 - R_1)^2 + (S_2 - R_2)^2 + \cdots + (S_N - R_N)^2}$$

If an AP is not present in one of the measurements, it is common to substitute its signal strength with either the minimal signal strength found in this measurement or with a fixed predetermined value.

There are several variations of the fingerprinting algorithm. A fingerprinting system based, for example, on the nearest neighbor (NN) algorithm estimates the location of a device to be the location of the measurement in the training radio profile with the smallest Euclidean distance to the current measurement. A *K*-NN algorithm produces an estimate of the device's location by averaging the locations of the K measurements in the training profile with the smallest Euclidean distance to the current measurement. The ideal K value can be determined through experimentation in a representative environment, but a small value of 3 or 4 was shown to work well in practice (Cheng et al., 2005).

7.2.3.6 Dead Reckoning

Dead reckoning is a location technique that computes the location of a device based on its previously known location, or fix, elapsed time, direction, and average speed of movement. The assumption behind dead reckoning is that the direction and the average speed of movement since the last fix is either known or can be estimated. Figure 7.5 illustrates the principle behind dead reckoning. The black dot represents the last known location of the device. Knowing the last fix, the direction, and the average speed, it is possible to estimate the new location of the device at the location of the gray dot.

Since dead reckoning calculates the *relative* position since the last fix, it is being used in combination with another location technology capable of calculating the absolute location of the device. Dead reckoning is thus often used to refine the estimates of another location system

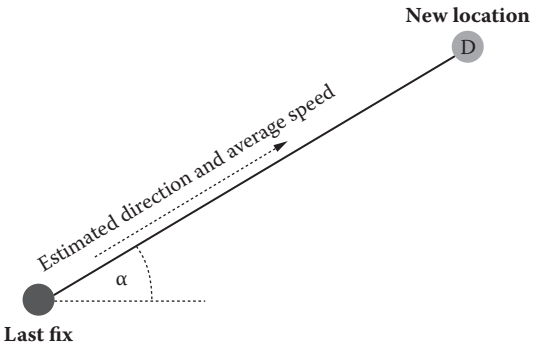

FIGURE 7.5 An example of dead reckoning in 2-D. The black dot represents the position of the last fix. The gray dot represents the estimated location of the device.

or to calculate the estimates when the other location system becomes temporary unavailable (e.g., when a car enters a tunnel and loses signals from GPS satellites).

The accuracy of dead reckoning depends on the quality of estimation of the speed and direction of movement. These can be estimated either through extrapolation from two or more previous fixes or measured by the sensors on the device itself. Some of the sensors that are often used for dead reckoning are accelerometers, which can be used to measure the acceleration of the device; odometers, which can be used to measure the distance traveled by a car; and gyroscopes, which can be used to measure the direction of movement.

7.2.4 Error Reporting

The goal of a location system is to produce accurate location estimates. Unfortunately, in practice, location systems often produce inaccurate estimates due to a variety of reasons. This section surveys some of the common reasons for errors in location systems and describes the common procedure for reporting location errors.

7.2.4.1 Sources of Errors

Location systems are designed to produce accurate location estimates given that the measurements that the location system uses are accurate as well. Unfortunately, there are several factors that introduce errors into location systems.

Incorrect reference point coordinates. Location systems that require the precise location of reference points produce location errors when the given locations are incorrect. This problem can be mitigated or eliminated for stationary reference points by carefully mapping the location of the reference points. However, for reference points that are mobile (e.g., GPS satellites) this may be a difficult problem due to unexpected factors (e.g., solar winds) that may alter a reference point's location.

Ionospheric and tropospheric delay. Signals traveling through the ionosphere and troposphere experience delays due to interactions with the Earth's atmosphere. Although there are mathematical models that try to estimate the delay, it stills accounts for the major part of error in GPS-based positioning.

Clock synchronization. Precise time measurement requires tight clock synchronization between the sender and the receiver of the signal, or between devices that transmit signals simultaneously. Existing synchronization algorithms reduce the effect of clock skews, but do not eliminate them completely. Clock skews are a common error source for all location systems that use time measurements for location determination.

Multipath. A signal traveling through space may arrive at the destination along several paths due to interactions with obstacles along the way. Copies of the signal may overlay at the receiver, causing distortions of the amplitude and phase of the signal. Having no line of sight between the sender and the receiver exacerbates the multipath problem, making measurement errors more severe.

Geometry. The configuration geometry of the reference points has an effect on accuracy. Positioning the reference points too close to each other or on a line typically results in large location errors.

7.2.4.2 Reporting Error

The quality of location estimates produced by a location system varies depending on many factors, including the physical location, the time of day, the current weather, and the environment. Therefore, to fully understand the quality of a location system, it is necessary to collect a large number of location estimates under various conditions. The procedure for reporting location errors depends on whether the location system produces symbolic or absolute locations.

Location systems estimating symbolic locations, such as home or work, produce estimates that are either correct or not. In this case, the most common means of expressing the accuracy of a location system is to present it as a percentage. For instance, a location system may determine the

room in a building correctly 85% of the time. Repeating the experiment several times allows for the calculation of confidence intervals of the accuracy of the location system.

For location systems estimating absolute locations, such as geographic coordinates, it is typical to show a cumulative distribution function of the location error. In this case, a location error is defined as the distance between the true and the estimated locations. It is also common to specify the 50th and the 95th percentile of the location error, both of which can be derived from the cumulative distribution function. If the location system performs differently along horizontal and vertical dimensions, then it is common to specify the location error separately for each dimension.

7.3 LOCATION SYSTEMS

The first part of this chapter discussed techniques and general concepts for building location systems. The remainder of this chapter discusses specific commercial and research location systems that use these principles and techniques. In addition, this chapter also attempts to highlight important characteristic that should be considered when applying a particular technology to an application.

Localization has been a very active research problem in the ubiquitous computing community in the preceding decade. Several characteristics distinguish the different solutions, such as the underlying signaling technology (e.g., IR, RF, load sensing, computer vision, or audition), line-of-sight requirements, accuracy, and cost of scaling the solution over space and over the number of objects. This section provides an overview of some of the historically important and current location systems and highlights the different characteristics of each system. The intent of this section is not to present an entire survey of location systems, but to highlight important historic and current systems that have addressed the general problem of location tracking in variety of ways.

It is important to note that there is no one perfect location system. Each system must be evaluated based on the intended application across a variety of dimensions such as its accuracy, the infrastructure requirements, the ability to scale, etc. Table 7.2 summarizes location systems covered in this section and dimensions that one should consider when evaluating, building, and using a location system. An important consideration is the performance or accuracy of the system and its resolution (e.g., low resolution for weather forecasts and high resolution for indoor navigation). At the same time, one must consider the infrastructure requirements to

TABLE 7.2 Location Tracking Technologies across a Collection of Factors Used to Evaluate a Particular Location System

	Location Type	Resolution, Accuracy	Infrastructure Requirements	Location Data Storage	Spectral Requirements	Location System Type
Active Badge	Symbolic Indoor	Room level	IR Sensors and customs tag	Central	IR	Custom active tagging
ActiveBat	Absolute Indoor	3 cm, 90%	Ultrasonic (US) receivers and transmitters	Central	30 kHz ultrasound and 900 MHz RF	Custom active tagging
ActiveFloor	Symbolic Indoor	1 m, 91%	Custom floor tiles	Central	Load sensor	Passive
Airbus	Symbolic Indoor	Room level, 88%	Single sensor in HVAC	Central	Pressure sensor	Passive
Cricket	Absolute Indoor	3 cm, 90%	US receivers and transmitters	Local	30 kHz ultrasound and 900 MHz RF	Custom active tagging
GPS	Absolute Outdoor	10 m, 50%	GPS receiver	Local	1500 MHz RF	Custom active tagging
PlaceLab (GSM)	Symbolic Indoor/Outdoor	20 m, 90% 5 m, 50%	Existing GSM towers	Local	900–2000 MHz RF	Active tagging
LaceLab (WiFi)	Symbolic Indoor/Outdoor	20 m, 50%	Existing WiFi APs	Local	2.4 GHz RF	Active tagging
PLP	Symbolic Indoor	2 m, 93% 0.75 m, 50%	2 plug-in module and custom tag	Local or central	300–1600 kHz RF	Custom active tagging
RADAR	Symbolic Indoor	6 m, 90% 2–3 m, 50%	3–5 WiFi APs	Local	2.4 GHz RF	Active tagging
Ubisense	Absolute Indoor/Outdoor	15 cm, 90%	Custom sensors and tags	Central	2.5 GHz and 6–8 Ghz wideband RF	Custom active tagging
Vision	Absolute Indoor/Outdoor	1 m, 50–80% (varies by camera density)	Multiple cameras	Central	RF for wireless cameras	Passive

Note that the accuracy is reported as a percentile.

evaluate the ease of deployment, cost and installation, and maintenance burden. For example, targeting location systems for the home presents several challenges. One major challenge is cost. In a commercial setting, more resources are typically available for disposal, and thus a company can justify the investment based on added productivity and reduction of other costs. On the other hand, the average homeowner would have difficulty justifying a high cost. Also, consider a researcher wanting to install location systems in various homes for a study. The cost of simultaneously deploying a system in multiple homes is much greater than a single, larger commercial building, such as an office building or a hospital, because parts of the infrastructure have to be replicated for each home being studied. Other important considerations are the spectral requirements of the location system. For example, certain parts of a hospital have very strict regulations on RF emission. Thus, in these environments, one may choose an IR-based solution. Another important consideration may be whether it is practical to have an individual carry a location tag. Finally, certain applications may require the protection of one's privacy, thus requiring a location system that computes its location locally as opposed to at a central server.

7.3.1 Global Positioning System

Currently, GPS is the most popular outdoor location tracking system worldwide. GPS first originated for military applications, but today, GPS-based solutions permeate throughout many civilian and consumer applications, such as in-car navigation systems, marine navigation, and fleet management services. Civilian GPS has a median accuracy of 10 m outdoor, but areas with substantial occlusions, such as tall buildings and large mountains can reduce the accuracy of the system. GPS typically does not work well in most indoor settings, because of constant occlusions from the GPS satellites.

GPS consists of receivers that passively receive signals being transmitted from a subset of at least 24 geosynchronous satellites orbiting the earth. Each GPS satellite transmits data that contains its location and the current time. Although the signals transmitted by the satellites are synchronized, they arrive at the receiver at different times due to the difference in distance between the satellites and the receiver. Thus, the distance to the GPS satellites can be determined by estimating the amount of time it takes for their signals to reach the receiver. At least four GPS satellites are needed to calculate the position of the receiver.

These GPS satellites transmit data over various radio frequencies, designated as L1, L2, etc. Civilian GPS uses the L1 frequency of 1575.42 MHz in the ultrahigh frequency band. This signal consists of three different pieces of information—a pseudorandom ID code, ephemeris data, and almanac data. The pseudorandom code is a simple ID code that identifies which satellite is transmitting information. The ephemeris data indicates to the GPS receiver where each GPS satellite should be located (orbital data) at a given time in the day. Finally, the almanac data contains information about the status of the satellite (healthy or unhealthy), current date, and time.

Unlike the GPS satellites, GPS receivers do not have atomic clocks and are not synchronized with the GPS satellites. Therefore, a GPS receiver calculates the time difference of arrival (TDOA) using the timing slack required to synchronize the GPS receiver's generation of a pseudorandom ID code with those being transmitted by the satellite to determine the signals' travel time. To determine its location, the receiver applies hyperbolic lateration in 3-D using the estimated TDOA values. In addition, a fourth satellite is required to correct any synchronization errors.

A GPS receiver also takes into account a variety of correction factors that may impact the signal delay. Here are some factors the can degrade the quality of the GPS signal originating from the satellites:

- Multipath—occurs when the GPS signal is reflected off tall buildings, thus increasing the time-of-flight of the signal.
- Too few satellites visible—occurs when there are major obstructions (e.g., GPS does not work well indoors or underground).
- Atmospheric delays—signals can slow as they pass through the atmosphere.

There are several ways to minimize some of these errors. One way is to predict and model the atmospheric delays and apply a constant correction factor to the received signal. The other strategy is to increase the number of channels in the receiver to allow for more satellite signals to be seen. A recent system, called differential GPS, uses a collection of terrestrial beacons to emit correction codes (using long wave radio between 285 and 325 kHz) in multipath-prone areas. The accuracy of differential GPS has been shown to be 1.8 m at least 95% of the time [youssef03]. Another approached called Real-Time Kinematic GPS uses phase measurements from existing GPS signals to provide receivers with real-time corrections.

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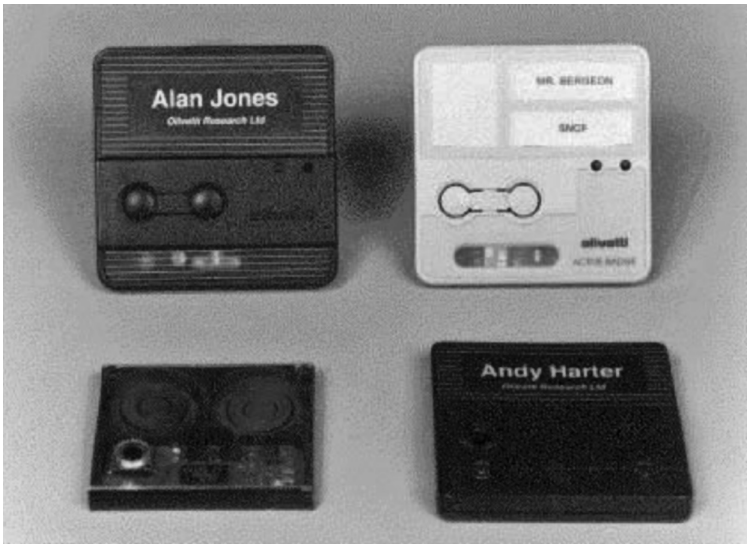

FIGURE 7.6 Original Active Badges used at Olivetti (http://koo.corpus.cam.ac.uk/projects/badges/index.html).

7.3.2 Active Badge

The Active Badge (Want et al., 1992) was first introduced by the Olivetti Research Laboratory in Cambridge and was one of the first indoor location tracking systems developed. The Active Badge is designed to be worn by visitors and employees of an organization to allow a central database to keep track of their location within the building (see Figure 7.6). The badge transmits a unique code via a pulse-width modulated IR signal to networked sensors/receivers deployed throughout a building. The Active Badge uses 48-bit ID codes and is capable of two-way communication.

The badge periodically beacons the unique code (approximately every 10–15 s), and the information regarding which sensors detected this signal is stored in a central database. The IR-based solution is designed to operate up to 6 m away from a sensor. The IR signal is strong enough to be reflected off walls and ceiling, so that sensors can detect these signals in a small room without line-of-sight operation. Since the IR signal does not travel through wall, the sensors are deployed throughout the space. The walls of the room can also be used as a natural boundary to contain IR signals, thus enabling a receiver to identify the badge within a room. The density and the strategic placement of the sensors also dictate the resolution of the location tracking. For example, multiple sensors may be

deployed in a large conference room to detect if the individual is near the podium or sitting at the table. The Active Badge system uses a lookup table in the central server for determining the location of the badge, based on which sensors are detecting the badge. This physical location is associated to each sensor with an initial setup and installation phase.

Based on the Active Badge system, other IR-based location tracking solution have also been developed, such as the SPECs project from HP Labs and the Versus system (http://www.versustech.com/). Although the disadvantage of these solutions is that they require line-of-sight operation, the use of IR allows for a low-cost and simple tag and receiver design.

7.3.3 Active Bat

Active Bat (Ward et al., 1997) is an ultrasonic-based location tracking systems consisting of ultrasound receivers dispersed in a space and location tags that emit ultrasonic pulses. Active Bat tags emit short pulses of ultrasound and are detected by receivers mounted at known points on the ceiling, which measure the time-of-flight of each pulse. Using the speed of sound, the distance from the tag to each receiver is calculated. Given three or more measurements to the receivers, the 3-D position of the tag can be determined using trilateration. One key concept of Active Bat is the use of an RF signal to cue the tag to transmit its ultrasonic pulse. The RF cue gives the receivers in the environment a starting point for timing the received ultrasonic pulse. Since the speed of light is significantly faster than the speed of sound, the RF signal delay is negligible and does not need to be considered for calculating the time-of-flight of the acoustical signal.

The information about the location of Active Bat tags is managed by a central server. This coordination is essential in garnering efficient use of the available ultrasound bandwidth among all the tags. Multiple tags must coordinate their pulses so as not to interfere with each other's time-of-flight calculations. In addition, multiple receivers are needed to ensure line-of-sight operation and to reduce multipath problems. Active Bat has a location accuracy of 90% at 3 cm. The system supports 75 tags being tracked in a 1000 m^2 space consisting of 720 receivers. Although Active Bat offers precise indoor location tracking, it does require significant instrumentation to the space.

One of the drawbacks of the Active Bat architecture is its active approach of the tag beaconing, as opposed to using a passive approach, where the tag listens to pulses emanating from the environment (see Figure 7.7). The

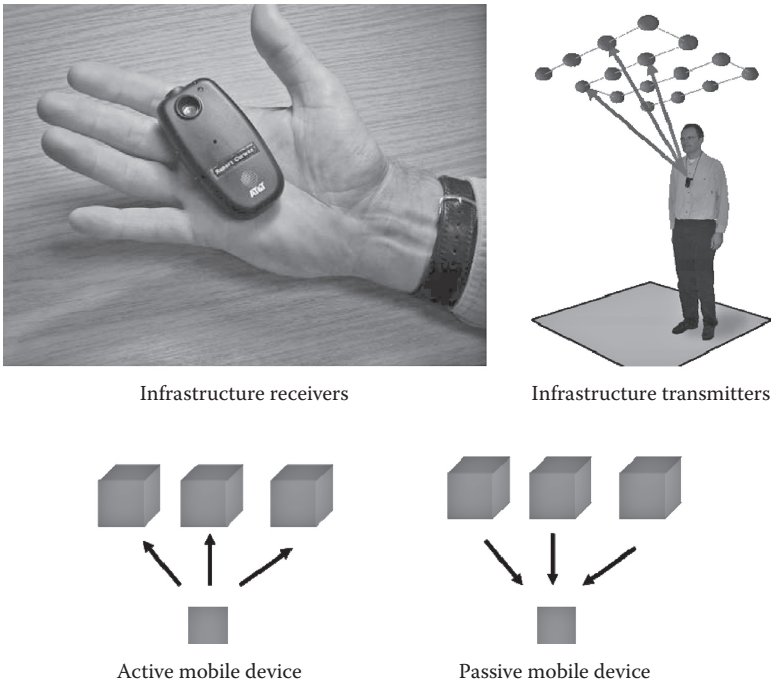

FIGURE 7.7 Top: Active Bat tags and example placement of receivers (http://research.microsoft.com/en-us/people/shodges/past.aspx). Bottom: Active (e.g., Active BAT) versus passive (e.g., Cricket) approach to location tracking systems.

passive architecture scales better than the active architecture as the density of location tags increase, because the RF and acoustical channels use is independent of the number of tags in the environment. In addition, the active mobile architecture requires a significant network infrastructure to connect the deployed receivers to a central server. This also leads to privacy concerns, because the central server knows the position of all tags in the systems. In contrast, the passive architecture allows a mobile device to estimate its location locally on each tag (see Cricket).

7.3.4 Cricket

The Cricket location system (Priyantha et al., 2000), unlike ActiveBat or ActiveBadge, does not rely on a centralized architecture to compute location information. Each Cricket tag is a small platform incorporating an RF transceiver, a microcontroller, and hardware receiving ultrasonic signals.

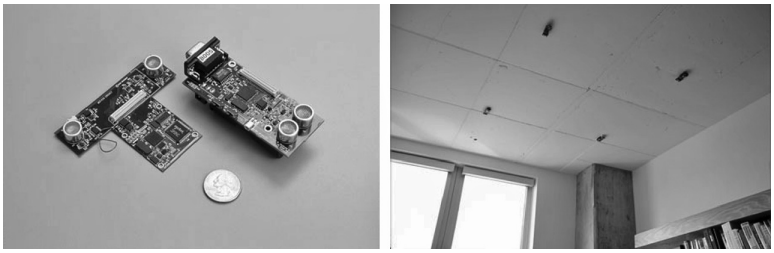

FIGURE 7.8 Cricket tags and example placement of the transmitters (http://nms.lcs.mit.edu/projects/cricket/).

Cricket beacons are affixed to known locations and are typically attached to the ceilings or walls of a building (see Figure 7.8). Each beacon periodically transmits a wireless (RF) message while at the same time sending a short ultrasonic pulse that allows the receiver tag to measure the distance from the beacon using the time-of-flight of the ultrasonic signal (similar to the technique used in Active Bat). The tag determines the time-of-flight of the acoustical signal and computes the position of the tags relative to the nearby beacons using trilateration. Each tag then uses these distance measures and the beacon position information contained in the RF messages to compute their location relative to the space. Since the tags do not actively transmit data, the scaling of the system is independent of the number of tags in the environment.

Unlike the ActiveBat system, Cricket is decentralized, so it preserves privacy by performing location calculations directly on the tag itself. In addition, the beacons deployed in the space do not have to be networked together, reducing some of the installation burden. Similar to the ActiveBat, line-of-sight operation is needed between each tag and at least three beacons, which requires sufficient installation of Cricket beacons to ensure full coverage in a space.

7.3.5 UbiSense

Ubisense (http://www.ubisense.net) is a commercial location tracking system using an ultrawideband (UWB) signal for localization (see Figure 7.9). Ubisense offers high precision at about 15 cm (at 90th percentile) by triangulating the location of active tags (called Ubitags) from a collection of networked sensors (called Ubisensors) distributed in a space. Each Ubitag incorporates a conventional RF radio (2.4 GHz) and a UWB radio (6–8 GHz). The conventional radio is used to coordinate and schedule when a

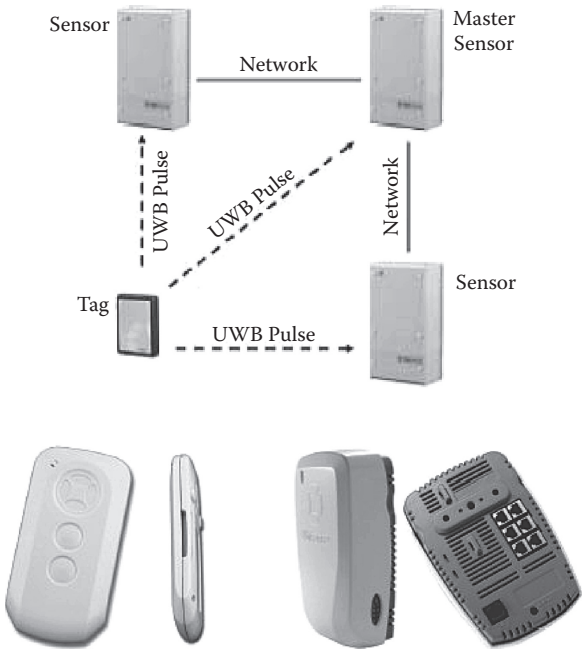

FIGURE 7.9 Top: Infrastructure architecture for Ubisense. Bottom: Ubitags are shown on the left and Ubisensor on the right (http://www.ubisense.net).

particular Ubitag should transmit its UWB pulse. The Ubisensors consist of a collection of phased array antennas.

After a tag is queried to transmit its UWB pulse, the Ubisense system uses TDOA and AOA to triangulate the location of the tag. Thus, at least two Ubisensors are needed to calculate the 3-D position of a Ubitag. The TDOA information is computed from sensors connected together with a physical timing cable. The advantage of using UWB pulses is that it is easier to filter multipath signals and can endure some occlusion. However, Ubisense does require line-of-sight operation for optimal performance. Since a timing cable is required to each Ubisensor, the installation process can be challenging in certain environments.

7.3.6 RADAR

The cost and effort of installation of the necessary infrastructure is a major drawback to wide-scale deployment of a location system. Thus, there have been efforts in developing location-based systems that reuse existing infrastructure to ease the burden of deployment and lower the

cost. The RADAR system implements a location service using the information obtained from an already existing 802.11 WiFi network (Bahl and Padmanabhan, 2000). RADAR uses the RF signal strength [also know as the received signal strength indicator (RSSI)] as an indicator of the distance between an AP and a receiver. The major advantage of this approach is that a consumer does not have to purchase any specialized equipment and can still benefit from a location-aware application. For example, existing devices, such as WiFi-enabled mobile phones, PDAs, or laptops, can be repurposed as a receiver or tag.

The initial RADAR system used a trilateration approach on the RSSI values, but problems with multipath led researchers to use a mapping or fingerprinting approach for localization, where an offline signal map is constructed before the operation of the system. The signal map consists of locations in a building and the signal strength of RF waves emanating from nearby WiFi APs. For example, at a location (x,y) there are signal values associated with that position, one for each detectable WiFi base station. The creation of this signal map involves a user walking to several different locations with a location tag in the building and recording the physical coordinates of each location together with the signal strength from each AP.

To determine the position of the WiFi-enabled device, the receiver measures the signal strength of each of the APs and then searches through the signal map to determine the signal strength values that best matches the signal strengths seen in the past. An NN approach is used to find the closest signal values and then the system estimates the location associated with the best-matching signal strengths.

Experiments with this approach have shown that RADAR has a median position error of about 3 m and 90 percentile resolution of 6 m. At least three APs are needed to be in range for effective localization. Some of the drawbacks of this approach are that changes in the environment (moving furniture, appliances, etc.) may change the signal propagation patterns in the space. This would require another site survey to be conducted to update the signal map. Some solutions to help reduce this problem are to use more APs and environmental modeling.

Based on the results of RADAR, many commercial WiFi-based indoor positioning systems have also emerged. Ekahau is a positioning system that offers 3 to 5 m resolution using six enterprise WiFi APs (http://www.ekahau.com). Similarly, Cisco also offers a fingerprinting-based location tracking services with their WiFi APs.

Another fingerprinting approach has looked at leveraging existing GSM cell towers to localize GSM mobile phones indoor (Varshavsky et al., 2007). Their approach fingerprints signal values of all available GSM channels to provide higher dimensionality to increase localization accuracy. Similar to WiFi localization solutions, a fingerprinting approach is used to determine the location of the device from a known signal map. This approach has a known median error of 5 m and a 90 percentile resolution of 15–20 m. Although this solution provides effective localization with little to no additional hardware to be deployed in an environment, one major drawback is that the user has very little control of the infrastructure itself. The performance of the system relies on publicly accessible infrastructure (e.g., GSM cellular towers), which can change over time. Service providers can adjust the operation parameters of the cellular towers with little warning, thus requiring an update to the signal map.

7.3.7 Place Lab

Place Lab (LaMarca et al., 2005) is a software-based indoor and outdoor localization system developed by Intel™ Research. Place Lab runs on commodity devices such as notebooks, PDAs, and mobile phones, and determines their position using radio beacons, such as 802.11 APs, GSM cell phone towers, and fixed Bluetooth devices that are already deployed in the environment (www.placelab.org). An advantage of Place Lab is that clients can determine their location privately without having to reveal information to a central service provider. In general, clients running the Place Lab software determine their location by detecting multiple unique IDs from these existing radio beacons and referring to a map of these devices.

PlaceLab's WiFi localization approach is very similar to RADAR and Ekahau, but there are two important distinctions. The aim of Place Lab is to provide location tracking at a large scale, whereas RADAR and Ekahau are primarily for smaller indoor environments. These approaches require calibration by the installer of the system. The aim of Place Lab is to use less dense calibration data that is contributed by a community of users so there is no need for an individual to populate a signal map.

Much of the Place Lab data is derived from the war driving community. War driving is the process of driving around with a mobile device equipped with a GPS receiver and an 802.11, GSM, and/or Bluetooth radio to collect traces of wireless base stations. Most of the war driving data is time-stamped recordings containing GPS coordinates and the associated signal strength of any beacons heard at the location. Wigle.net and

Worldwidewardrive.org are some examples of war driving repositories that contain millions of known APs. These data are used to estimate the position of the wireless beacons using a centroid approach, which estimates the position of the device to be a weighted average of positions of the overheard beacons. Although this approach only infers the location of the beacons, it has the added benefit that millions of beacon estimates have already been determined. Thus, this allows the ability to scale a location tracking system much more quickly despite the loss in accuracy. This approach has shown a median accuracy of 20–30 m in large cities

A similar effort was also started in Japan by the Sony™ Computer Science Laboratory called PlaceEngine (http://www.placeengine.com/en). PlaceEngine provides a mechanism for a community of users to update 802.11 beacon positions and the ability to track the location of any WiFi-enabled device. Place Lab also inspired commercial products such as Skyhook (http://www.skyhookwireless.com/) and Navizon (http://www.navizon.com/).

7.3.8 PowerLine Positioning

Inspired by this strategy of leveraging existing infrastructure and recognizing that there are drawbacks to relying on public infrastructure or the deployment of many beacons, PowerLine Position (PLP) was developed to provide indoor localization that would work in nearly every building (Patel et al., 2006b; Stuntebeck et al., 2008). With the significant insight being to use the power line as the signaling infrastructure, PowerLine Positioning is the first example of a whole-house or whole-building indoor localization system that repurposes the electrical system. PLP requires the installation of two small, plug-in modules for every 1000 m^2. In a home, only two modules would be necessary (see Figure 7.10). These modules inject a mid-frequency (300–1600 kHz), attenuated signal throughout the electrical system of the home. Both modules continually emit their respective signals over the power line, and location tags equipped with specially tuned tags sense these signals in a building and relay them wirelessly to a receiver in the building. Depending on the location of the tag, the detected signal levels provide a distinctive signature, or fingerprint, resulting from the density of electrical wiring present at the given location and the distance from the plug-in module. PowerLine Positioning is capable of providing subroom-level positioning for multiple regions of a building. The current PLP system has median error of 0.75 m and a 90 percentile accuracy of 1 m.

One drawback of PLP is that it requires a complete site survey to be conducted before the deployment of the system (similar to WiFi- and GSM-

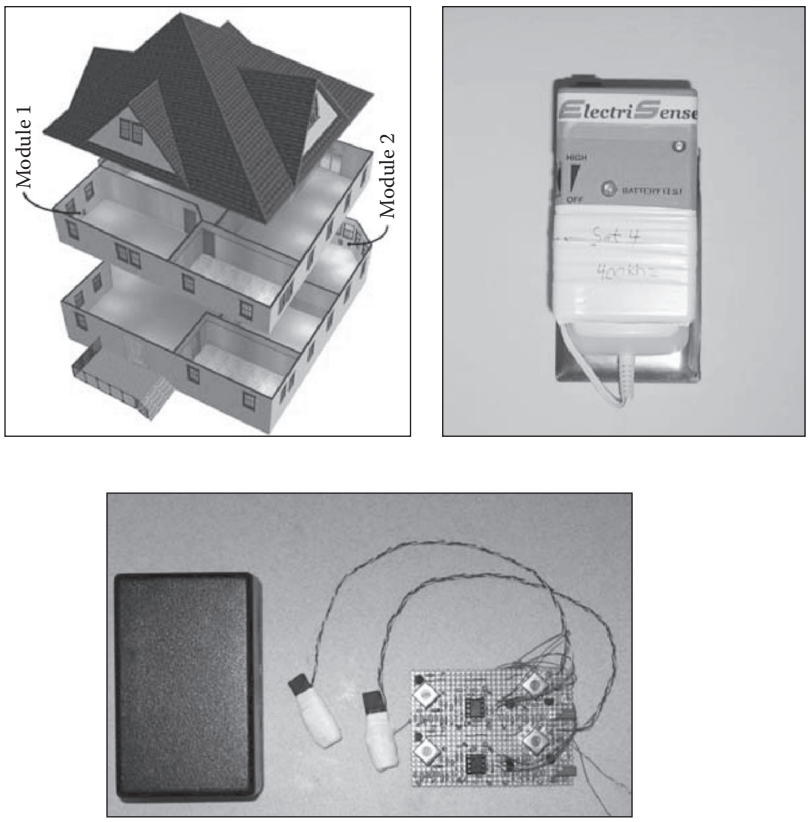

FIGURE 7.10 Top left: Placement of two signal-generating modules at extreme ends of a house. Top right: Signal generator plug-in modules. Bottom: Prototype PowerLine Positioning tag.

based fingerprinting solutions). However, the minimal infrastructure requirements and potential lower deployment costs is an important consideration for low-cost application, especially those that may be deployed in a home.

7.3.9 ActiveFloor

Many of the location tracking solutions discussed in this chapter require the attachment of a specialized tag to a device or a person carrying the tag. In addition, some of these tags require line-of-sight operation, which constrains where and how the tag is placed on a device. The tags also have to be associated with the attached device in a database. Because of these constraints, the tagging-based solution may not be appropriate for some

applications. ActiveFloor is one example of a location tracking technology that is designed to locate a person in a space without an individual having to carry or wear a special tag (Addlesee et al., 1997). ActiveFloor consists of load sensors embedded within floor titles. The location trace of a person is determined through the weight distribution throughout the floor. Although ActiveFloor does not require a tag to be carried by a person, it does require significant instrumentation to a space.

ActiveFloor uses 50 cm square plywood floor tiles supported by load sensors distributed across an entire floor (see Figure 7.11). The load cells are sampled at 500 Hz, which is sufficient for most walking and running activities. The static weight of the floor and the systematic errors are calibrated out by capturing sensor values with no additional weight being applied to the surface. When an individual walks on the surface, the reaction that the load sensors produce in response to the weight and inertia of a body in contact with the floor is called the ground reaction force (GRF) (in this case, the person's foot). As a person walks on the floor, the GRF values from each load sensor can be averaged to find the location of the mass. In addition, as a person steps on the tile, the GRF is not always constant, because individuals push of with their toe and plant their heel (heel strike)

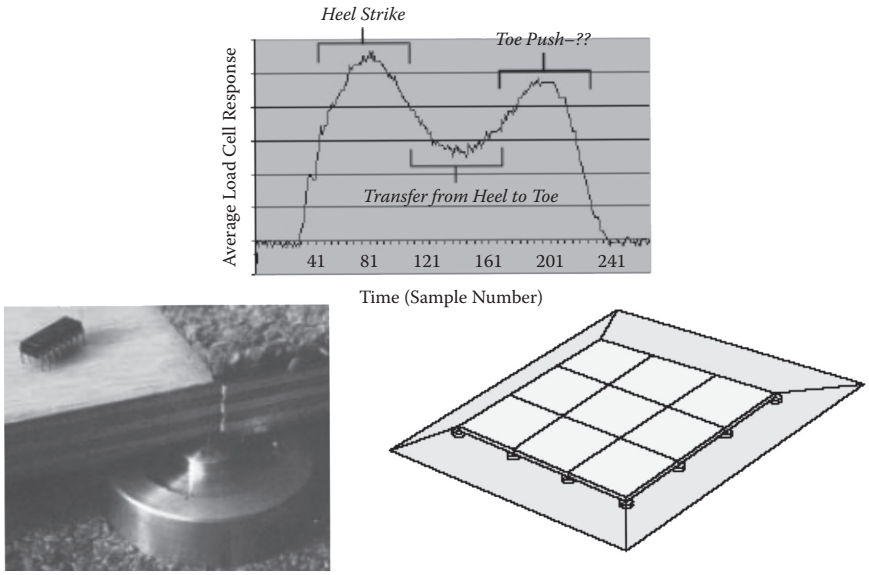

FIGURE 7.11 Top: GRF response of a single footstep. Bottom: Load sensor supporting a floor tile (http://www.cc.gatech.edu/fce/smartfloor/).

as they walk. This heel-to-toe transfer time and heel/toe GRF values can be used to calculate a footstep signature. ActiveFloor uses these features from the footstep signatures to build a hidden Markov model in order to identify the person. For further reading, a similar approach is also used by the Smart Floor project (http://www.cc.gatech.edu/fce/smartfloor/).

7.3.10 Airbus

Recent work has looked at providing passive tracking of individuals without having people carry a tag, similar in spirit to ActiveFloor. New strategies have tried to greatly reduce the amount of additional infrastructure needed for deployment. Airbus (Patel et al., 2008) is a location tracking system capable of detecting gross human movement and room transitions by sensing differential air pressure in a home (see Figure 7.12). The solution leverages central heating, ventilation, and air conditioning (HVAC) systems present in many homes. The home forms a closed air circulation circuit, where the HVAC system provides a centralized airflow source and a convenient single monitoring point for the entire circuit. Disruptions in home airflow caused by human movement through the house, especially those caused by the blockage of doorways and thresholds, result in static pressure changes in the HVAC air handler unit. The system detects and records this pressure variation using differential sensors mounted on the air filter and classifies where certain movement events are occurring, such as an adult walking through a particular doorway or the opening and closing of a door. Results have shown that the system can classify the opening and closing of specific doors with up to 80% accuracy with the HVAC in operation and 68% with the HVAC not in operation using support vector machines. These door events are used to compute a trace of where an individual is moving through the space.

An alternative strategy might be to install a collection of motion detectors in a space to directly sense the presence of a person to determine the path of a person (Wilson and Atkeson, 2005). This solution is more accurate than Airbus and would be necessary for environments that are not equipped with an HVAC system. The motion detector approach would also provide more resolution depending on the density of the installation. However, the other tradeoff is that the HVAC approach is much less obtrusive than installing motion detectors throughout a living space. Although the HVAC sensing provides location information at a lower fidelity than other tagging-based solutions, it does not require a person to carry a

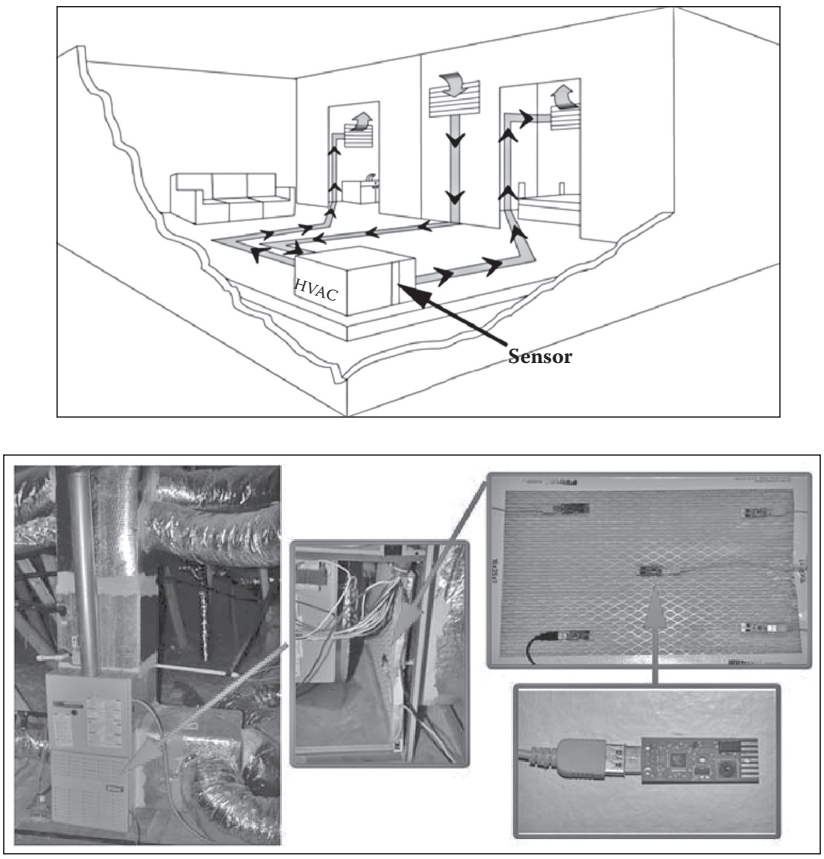

FIGURE 7.12 Top: Diagram of airflow from return and supply ducting in a home. Bottom: Instrumentation of a standard HVAC air filter with pressure sensors able to detect airflow in both directions. The air filter is then installed in the HVAC's air handler unit.

location tag and there is only a single location where the sensors reside and that has to be maintained. However, this technique does not work well for determining the identity of a person in a building. Airbus is more appropriate for applications that need to know people's presence, such as for smart heating and cooling or lighting control.

7.3.11 Tracking with Cameras

Another popular strategy to tracking the location of people is the use of cameras and computer vision techniques. The advantage of this solution is

there is no requirement for a person to carry a specialized tag and it is possible to leverage existing cameras typically found in many environments (e.g., surveillance cameras, closed-circuit television, etc.), reducing the deployment burden. Existing solutions have looked at using stereo camera images for locating the position of people in a space, and the color images for inferring identities (Krumm et al., 2000). To determine the distance to any point in the environment in a stereo vision system, a stereo camera identifies where that point appears in both camera views. Traditional stereo vision algorithms (Forsyth and Ponce, 2002) rely on distinctive textures in the pair of images to determine which points from the left camera image corresponds to a particular point in the right camera image. This provides additional depth information to the color information already present in a single camera's view. Blob detection and background subtraction techniques are used to infer the location of moving object (usually people) in the camera's view. Nonoverlapping cameras can also be used to provide location information on a planar surface (i.e., using overhead cameras) (Yang and Bobick, 2005). In addition to color histograms, more advanced face recognition approaches are used to determine the identity of a tracked person.

Although camera-based tracking provides an attractive solution for environments that may already have a deployed camera infrastructure, there are some drawbacks to this approach. The effective tracking range is limited to the field of view of a camera and covering large spaces requires coordination between adjacent views from multiple cameras. Similar to IR- and ultrasonic-based solutions, this approach does not work well in environments where there might be numerous occlusions. Tracking the position and the trajectory of a person in a fairly open space works well when using a camera, but tracking objects that might reside in cabinets and drawers would require a different technique. Finally, the stigma and privacy concerns associated with cameras may hinder the adoption of these techniques for certain applications.

7.4 CONCLUSIONS AND CHALLENGES

This chapter introduced the basics concepts of location technologies and surveyed some of the current and historical location systems. Furthermore, it described the differences between client-based and network-based positioning and identified some of the major sources of error in location systems. Finally, this chapter ends with a discussion of some of challenges and opportunities facing developers of location systems.

There is no single location technology today that is ubiquitous, accurate, low-cost (in terms of required hardware and installation), and easy to deploy. Although a novel location technology that fits all these parameters might still become available in the future, a more realistic approach is to combine several of the existing technologies into an integrated location system. For instance, although the median error of GPS is 10 m, the combined solution of GPS and European's global navigation satellite system called Galileo (as soon as it comes online) should yield a median accuracy of 1.5 m.

Developers of location-aware applications are faced with the challenge of building and maintaining location-aware middleware and location-aware back end services from limited existing solutions. These include collecting and reasoning about low-level sensor readings, storing location information on the back end servers, and making the information available to third-party applications in a scalable and privacy-preserving manner. Although there are several existing middleware and back end solutions available today (FireEagle; Hong and Landay, 2004), there is no well-accepted standard that is widely available for application developers.

Privacy remains as one of the main challenges for the proliferation of location services (Krumm, 2008). There is a need to hand over the control of location information disclosure to the user, without overwhelming him/her with privacy configuration, while still providing useful location services. For example, a recent study showed that users want plausible deniability in a location system (Iachello et al., 2005). Another study showed that people's preferences for disclosing location information differs based on many parameters, including the location of the user and the other person, the current user activity, and the relationship between the user and the other person (Consolvo et al., 2005). Refer to Chapter 4 for further discussion on user privacy in ubicomp.

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