

# Location-Aware Computing Comes of Age

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**A**t the core of invisible computing is *context awareness*, the concept of sensing and reacting to dynamic environments and activities. Location is a crucial component of context, and much research in the past decade has focused on location-sensing technologies, location-aware application support, and location-based applications. With numerous factors driving deployment of sensing technologies, location-aware computing may soon become a part of everyday life.

## LOCATION-SENSING TECHNOLOGIES

A central problem in location-aware computing is the determination of physical location. Researchers in academia and industry have created numerous location-sensing systems that differ with respect to accuracy, coverage, frequency of location updates, and cost of installation and maintenance.

### Coarse-grained systems

For applications in open, outdoor areas, the Global Positioning System is a common choice. A GPS receiver estimates position by measuring satellite signals' time difference of arrival. Although GPS offers near-worldwide coverage, its performance degrades indoors and in high-rise urban areas, and receivers have a relatively long start-up time and high cost.



**The widespread deployment of sensing technologies will make location-aware applications part of everyday life.**

In 1989, Roy Want, Andy Hopper, and others pioneered the study of indoor location sensing with their infrared-based Active Badge system. This provides room-grained location using wall-mounted sensors that pick up an infrared ID broadcast by tags worn by the building's occupants.

Many of the location-sensing systems developed since then are based on radio. By using base station visibility and signal strength, it is possible to locate Wi-Fi-enabled devices with accuracies from several meters to tens of meters. Bluetooth technology, which offers a shorter range than Wi-Fi, can give more accurate positioning, but at the expense of requiring more fixed base stations to provide coverage. Inexpensive radio-frequency identification tags can be used for location determination as well by placing RFID readers at doorways and other strategic points to detect the passage of people or objects.

Location information can also be derived from other types of RF infra-

structures, including those for mobile phones and TV broadcasts. These can be deployed over a wide area with relative ease, in contrast to technologies such as RFID that have limited transmission range. With mobile phones, Cambridge Positioning Systems has demonstrated location accuracies of 20 meters, while Rosum has achieved accuracies from 3 to 25 meters with digital TV signals.

### Fine-grained systems

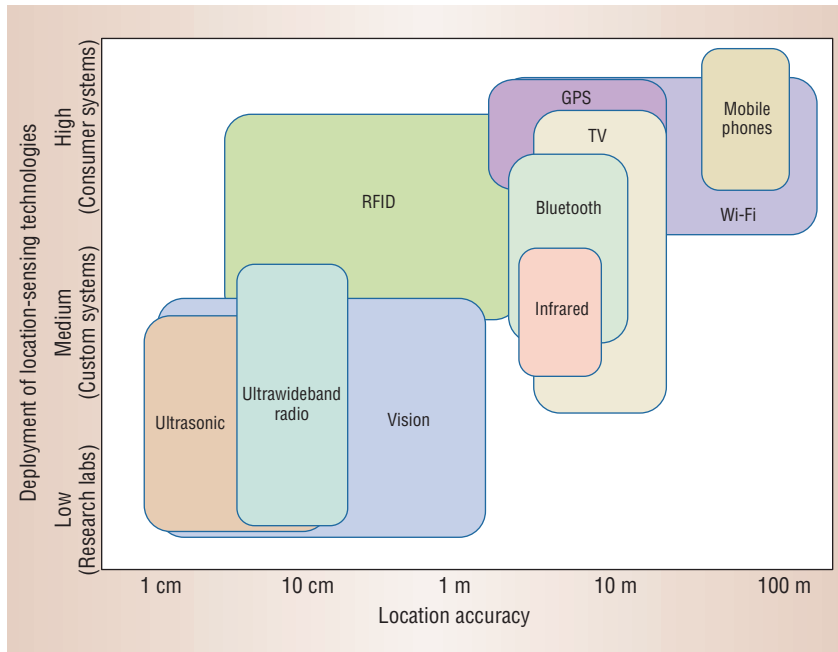
Many of the above systems are based on technologies that were not developed with location sensing in mind. Perhaps as a consequence they exhibit

modest accuracy, generally measured in meters. However, at least three types of systems have been designed specifically to provide fine-grained location sensing, achieving accuracies on the order of centimeters.

Ultrasound can be used to determine distances between mobile tags and known points in the environment. A process akin to triangulation can then be employed to derive a location estimate for the tag. One type of ultrasonic ranging device is the Cricket indoor location system developed at MIT, which is set to become available for purchase from Crossbow this year.

Some computer vision-based systems are appealing because they do not require users to wear any sort of tag. However, such systems have difficulty identifying and simultaneously tracking many subjects. Vision-based systems using barcode-like tags tend to be more robust.

Ubisense, a company that builds real-time local positioning systems,



**Figure 1. Location-sensing technologies.** Each box's horizontal span shows the range of accuracies the technology covers; the bottom boundary represents current deployment, while the top boundary shows predicted deployment over the next several years.

recently demonstrated a fine-grained tracking system that uses ultrawideband radio signals. Unlike conventional radio signals, these signals can have pulse durations short enough to allow accurate time-of-arrival and angle-of-arrival measurement, with an accuracy of about 15 centimeters. In addition, ultrawideband technology does not require a direct line of sight between tags and sensors.

## DEPLOYMENT

Figure 1 shows the current and predicted deployment of location-sensing technologies within the next two to three years. The widest existing deployments are based on GPS, which is particularly suited for outdoor applications. These include servicing applications centered on vehicle location such as route planning and fleet tracking, as well as applications integrated into handheld GPS units.

Other current deployments are found in vertically integrated solutions and comprise a specific location-aware application, appropriate location-sens-

ing hardware, and a custom software platform. A handful of firms offer these systems in targeted application areas such as military training, human-body motion capture, supply chain management, and asset tracking.

Looking ahead, numerous factors are accelerating the adoption of coarse-grained location-sensing technologies. To begin with, the recent explosion of Wi-Fi, Bluetooth, and other wireless networking technologies has led to many end-user devices being equipped with RF hardware that can be used for location sensing.

In addition, the Enhanced 911 requirement—which mandates that US wireless carriers provide location accuracies of 50 to 100 meters for emergency 911 calls by the end of 2005—is driving incorporation of location-sensing systems into mobile phones using GPS, base-station triangulation methods, and a combination of these technologies known as Assisted GPS. Similar requirements exist in the European Union.

Another important factor is a direc-

tive by US retail giant Wal-Mart that requires its top 100 suppliers to include RFID tags in their products by January 2005. Current plans call for tagging items by the case, but this may be extended to the tracking of individual items in the future.

In addition to the deployment of sensing technologies, increased hardware and software support is available for location-aware applications. For example, mobile phones have emerged as a ubiquitously deployed computing platform capable of downloading and running location-aware applications. Also, Microsoft recently revealed that its next PC operating system, code-named Longhorn, will include location-aware software components.

## ABSTRACTING LOCATION

To provide support for a variety of location-aware applications, researchers are working on techniques for fusing data from multiple sensors, on methods for representing location data, and on drawing high-level contextual information from location data.

## Sensor fusion

Vertically integrated location-aware systems typically use one type of sensor for a single application. However, in the near future, many kinds of location sensors may be available to a particular client system. The task of making sense of this vast amount of sometimes contradictory information, known as *sensor fusion*, presents a major challenge.

Borrowing from the field of robotics, location researchers have settled on Bayesian inferencing as the preferred method for processing data from disparate location sensors. Using Kalman filters, hidden Markov models, dynamic Bayes nets, and particle filters, they have developed principled methods of incorporating sensor uncertainty as well as limits on speed and travel paths.

The result is a location measurement derived from multiple sensors and constraints that uses a probability distribution rather than a single value to

describe the inherent uncertainty. For example, researchers at the University of Washington have demonstrated an indoor location-measuring system that processes data from multiple sources, including infrared and ultrasonic sensors, using a particle filter. In addition, the system learns typical walking paths through the building to aid in location estimation.

## Representation

Finding a way to represent location readings that facilitates storage, communication, and interpretation is also a challenge. Unfortunately, no single representation is useful in all circumstances.

Sensors tend to report locations as numerical coordinates such as  $(x, y, z)$ , but semantic representation is more effective for application-level reasoning about locations. Semantic representations usually include a hierarchy of locations such as (building, floor, room) or (country, state, city), and, like numerical representations, also must include a notion of uncertainty.

Some applications, such as travel planners, require both types of representations: Map-like coordinates are needed to perform Euclidian distance calculations, while information about terrain, traffic patterns, customs procedures, and other factors is important to achieve accurate travel-time projections. Due to the varying types of measurements from different sensors and the varying requirements of different applications, no dominant representation for location has emerged.

Sensed locations are useless without a *location authority* that gives a space of possible locations and can respond to queries about distances, routes, and proximity. Example location authorities include WGS84 data for latitude/longitude and maps or floor plans in computational form.

## Place and context

Simply knowing that a person is “at home,” “in my office,” or “in my car” is often sufficient for applications to carry out predetermined actions in a

given situation, such as turning off a cell phone’s ringer during a film or concert. In these cases, the person’s relationship or interaction with a place is more important than the physical location.

Toward this end, location data can be used to infer higher-level contextual information. For example, University of Washington researchers have used a time sequence of GPS data to infer a

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person’s mode of transportation—foot, bus, or car. Others working at MIT have developed a location-aware augmented-reality museum guide that classifies a visitor’s movement patterns as “greedy,” “busy,” or “selective” and tailors its content accordingly.

## APPLICATIONS

In addition to specialized applications such as military training and asset tracking, location-aware applications have been developed for a number of everyday scenarios:

- office applications such as nearest-printer services and mobile desktop control can increase workplace productivity;
- tour and museum guides can help people navigate an unfamiliar space;
- “locate my friends” utilities can be linked with instant messaging for social or business purposes;
- conference aids can track presentation attendance and facilitate note taking and discussion;
- medical facilities can track staff and monitor patients for emergency response; and
- home applications can help with household management and home entertainment, as well as aid the aged and disabled in performing everyday tasks.

While coarse-grained location-sensing deployments will enable some of these applications, others will require fine-grained location-sensing systems. The deployment of this additional infrastructure will rely on an adequate return on investment. Unlike some technologies, fine-grained location-aware computing does not appear to have a “killer app” to provide the required economic incentive. However, the combination of benefits that many applications provide might justify widespread adoption.

**A**dvances in location-sensing technologies and factors promoting wide-scale deployment will soon make coarse-grained location information widely available. Recent achievements in sensor fusion techniques, location representation, and software support will facilitate the development of applications that can use this multitude of sensors. In time, fine-grained location systems and applications will become more economically viable.

For more information on location-aware computing, visit [www.cambridge.intel-research.net/lac/links.php](http://www.cambridge.intel-research.net/lac/links.php). Many of the research examples discussed in this article were presented at the 2003 Workshop on Location-Aware Computing, held as part of the 5th International Conference on Ubiquitous Computing in October 2003. ■

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