Tradeoffs in Location Support Systems: The Case for Quality-Expressive Location Models for Applications

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Abstract. Location support systems typically tradeoff positional accuracy, uncertainty, and latency in providing location information for ease of configuration, lower hardware costs, energy-efficiency, scalability or preserving user privacy. In this paper, we explore these tradeoffs by discussing the design space of location support systems and their impact on applications. Applications informed of these tradeoffs can adapt to them and substantially improve their performance. Location models and abstractions should therefore be quality expressive *i.e.,* provide an explicit representation of parameters such as accuracy, timeliness, energy costs of location information.

1 Introduction

Possessing a unique location, a user can seek, offer or be offered resources on the basis of where she is located. A user could request a resource or service (eg., a printer) closest to her current or expected future location. Likewise, applications could use the user's location or travel itinerary to access cached data or to search for information about specific geographical areas. Queries about a service within a given radius of a specified location could be directed to a limited number of servers in the region without flooding the entire network.

Elevating location to the rank of a first-class system object enables many new kinds of service, from transparent pointcasting (newspaper delivery to one's doorstep, wherever it might be) to emergency services (distress calls that identify the caller's location). By revealing a node or user's expected location at a future time, it would be possible to offer prestaged delivery of specific information without requiring the node to request explicitly the information upon arrival. Such prefetching can greatly reduce the user's perception of latency.

Fundamentally, such context-aware and location-dependent applications use a location model to map the *physical location* of a user or node in some coordinate system provided by the location support system to a *logical location i.e.,* proximity to one or more nearby objects or services.

Our research falls under the realm of wireless sensor networks [2]. We view a location support system as a wireless sensor network of several nodes, each with diverse sensors, that trades off accuracy, timeliness in providing location with a physical measurement of the system. Because application requirements tend to be fairly diverse, there is "no one size fits all" approach to providing location support. Nevertheless, a single location system is often used to support several applications. Therefore, applications should be aware of these tradeoffs and tune their performance accordingly.

In this paper, we discuss the design space of location support systems, and provide some case studies of location support systems to argue for a *quality-expressive* location model, one that encapsulates not just the granularity of the location information but also other parameters including timeliness and energy costs. This paper is not intended to be a comprehensive survey of location support systems or even of the tradeoffs involved. However, we hope that an understanding of these issues will enrich both the design of location models and the generalizability and performance of the applications it could support. In summary, we believe that any general location model should satisfy the following requirements.

- Be applicable to a wide range of location-support systems.
- Encapsulate a general notation which facilitates communciation between users of different types of location-support systems.
- Provide a definition of performance and practical methods of measuring that performance.
- Establish an upper limit to the theoretical performance of a system.
- Provide a way of specifying location-support systems which allows greater flexibility to the designer by not pre-judging technical issues.

2 Tradeoffs

The design space of location support systems is inherently huge as it involves several complex factors including the type of operational environment (indoor or outdoor), number of devices , nature of applications, device hardware and networking heterogeneity and cost requirements and capabilities. In this section, we discuss some of these design tradeoffs.

2.1 Accuracy

From an application perspective, positional accuracy is often the most fundamental concern. Application support depends on whether its required positional accuracy can be provided by the location support system. For instance, even within the context of wireless sensor networks [2], geographic ad hoc routing requires location accuracy to be on a scale with range, whereas collaborative signal processing applications may require precise position information [3]. Providing precise location information requires dedicated hardware, higher power, extensive pre-configuration or centralized approaches. Therefore, a location system may be engineered to support only a certain desired location granularity. Applications with lower granularity requirements can further improve their performance by leveraging this finer grained location information. For instance, with fine-grained position information the energy-efficiency of a geographic routing algorithm could be further improved by adjusting the transmission power to only reach the intended next hop of a message and no further.

The location model should therefore incorporate not just the position but *positional accuracy.* Accuracy itself has two metrics: (1) *resolution* - which gives the mean position error (distance between measured and actual position) and (2) *precision* - how often the estimated position error lies within the resolution(mean position error).

2.2 Sensing Modalities

Location information is usually obtained using diverse sensors - passive or active infra-red, acoustic, radio-frequency and image sensors. Each of these sensing modalities affects the uncertainty in location in a different way. For instance, range or amplitude sensors have high uncertainty along the axis perpendicular to the direction of motion of the observed object whereas bearing sensors have lower uncertainty along this axis. Combined acoustic and radio ranging is affected by non line-of-sight conditions, but provides highly accurate line-of-sight ranging [3]. The location model could therefore *qualify uncertainty* along each axis, or provide a probability distribution function (PDF) for location, if a compact representation exists.

2.3 Energy Constraints

For several applications, nodes and beacons often need to be small and untethered, imposing substantial energy constraints. Energy constraints heavily influence system design. The consequent low-power design often comes at a price of functionality. At the hardware level, low-power design may include using fewer sensor modalities per node (for instance, purely RF-based localization systems[1]). At the system level, these energy considerations could also influence beacons to turn themselves off or operate at a lower duty cycle. Or special sensors such as tilt sensors may be employed to sense movement, to restrict location computation only when object movement is detected. The location model should therefore include information such as the *frequency* of location updates or the *energy expended* per location update as a function of the resolution required.

2.4 Orientation

The ability to determine the orientation of a device can greatly enrich context-aware and location-dependent mobile computing. Knowledge of orientation of a mobile device enhances various applications, including efficient way-finding and navigation, directional service discovery and "augmented-reality" displays. The location model should also expose the *orientation* and *orientation* information when available. However, computation of orientation itself may require finer-grained position information.

2.5 Federation of multiple spatial coordinate systems

It is extremely challenging to engineer a location system that provides fine-grained position information in a global scope. Applications often need to integrate location information obtained from multiple coordinate systems. This requires a framework for representation of location information from various sources, such as satellite navigation systems, wireless positioning technologies, beacons, indoor navigation systems, human input etc. These sources all operate at various degrees of accuracy and often suffer from independent errors. Their output in terms of the location, can be represented more generally as a probability density distribution (PDF) of the location over a two or three dimensional space - typically Cartesian or other coordinates. Combining two or more such PDFs yields a more accurate PDF of the location and improves navigation under difficult circumstances such as indoors or in fading environments. The location model should provide a way of representing the *coordinate system frame* in which the location is expressed, and a *transformation function* to tranform that location to another coordinate system, if necessary.

2.6 Dynamic Environments and System Self-Configuration

Location systems often rely on extensive pre-configuration to provide accurate position information. Unfortunately, this can affect its reliability, robustness and performance in dynamic environments. Some applications may desire a location-support system that provides the desired location support in terms of resolution and latency required, despite significant dynamics such as environmental obstructions, system or node failures or even object dynamics (for example, mobile users). For instance, many positioning systems assume that the positions of beacons or reference nodes are pre-configured. An important system capability would be for beacons to cooperatively determine ranges to each other and independently form a coordinate system, however this would require fairly sophisticated capabilities in beacons [3]. Because the quality of location information can significantly vary with dynamics, the location model should provide a way to extract both statistical distributions and raw location information. If the location model can expose the current quality of service, applications would also be able to give feedback (implicitly or explicitly) to the location-support system, so that it can provide better quality.

3 Case Studies

The Global Positioning System (GPS) [4] has been around for almost 20 years. Because GPS does not work indoors, a number of prototype indoor positioning systems have been proposed in the past few years [1]. In this section, our case studies focus on three different location systems that employ the same ranging technique but have significant architectural differences. The ranging technique exploits the vastly different speeds of sound and radio signals, using a radio signal for time synchronization and a concurrently emitted but slower acoustic signal for calculating time-of-flight, and consequently distance between two points.

3.1 Active Bat

Active Bat [7] is the earliest prototype indoor ultrasonic location system. It uses passive ceiling-mounted beacons that listen to concurrent radio and ultrasonic pulses from an Active Bat device. It relies on tight synchronization amongst beacons, centralized control and careful beacon positioning to achieve very high accuracy (a few cm). The fine-grained accuracy of Active Bat enables several exciting applications. The laboratory's telephone system can divert phone calls to the receiver nearest the badge wearer. It can also send e-mails to the nearest terminal.

3.2 Cricket and the Cricket Compass

Cricket [5] is an ultrasonic location system for pervasive computing applications akin to Active Bat, albeit with different design goals. Cricket is decentralized. Therefore, rather than the system tracking the user's location, each portable device determines its own location. The emphasis was on ease of deployment and preserving user privacy with more modest accuracy goals (correctly identify regions within a room). These design decisions have several performance implications besides lower accuracy. For instance, decentralized coordination amongst beacons requires that Cricket beacons transmit position advertisments at a much lower frequency, in order to avoid interference amongst several beacons vying for the same transmission slot. This affects the perceived user latency.

On the other hand, the Cricket Compass [6], an extension of the original Cricket location support system that provides position and orientation, requires careful positioning both of fixed beacons and passive ultrasonic sensors that compute location, therefore sacrificing its ease of deployment. This is because determining orientation requires sub-cm positional accuracy [7, 5].

3.3 Multimodal Localization System

The multimodal localization system [3] is intended to support applications such as unobtrusive habitat monitoring using wireless sensor networks. A typical task here would be passive detection and tracking of birds by a number of distributed sensors based on collaborative signal processing of acoustic signatures. Here the goal is to provide a location support system that is not only fine-grained like the Active Bat (sub-cm accuracy), but is also ad hoc deployable, like the original Cricket. Camera imaging to used to detect and eliminate non line-of-sight readings in acoustic ranging. An additional sensing modality (camera) makes it possible to achieve a location system that is simultaneously ad-hoc deployable, decentralized, and fine-grained.

4 Conclusions

Location support systems typically tradeoff positional accuracy, timeliness in providing location information and other capabilities for scalability, ease of configuration, energy-efficiency and small form factor, low cost hardware. Moreover, location support systems often support multiple applications and therefore cannot be customized to the needs of a particular application. Applications that are informed of these tradeoffs can perform better. However, such information is often provided implicitly. Location models and abstractions should be quality expressive *i.e.,* provide an explicit representation for these parameters to allow applications to be effective and portable without being tied to a particular location-support system.

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