A Survey of Indoor Positioning Systems for Wireless Personal Networks

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***Abstract*—Recently, indoor positioning systems (IPSs) have been designed to provide location information of persons and devices. The position information enables location-based protocols for user applications. Personal networks (PNs) are designed to meet the users' needs and interconnect users' devices equipped with different communications technologies in various places to form one network. Location-aware services need to be developed in PNs to offer flexible and adaptive personal services and improve the quality of lives. This paper gives a comprehensive survey of numerous IPSs, which include both commercial products and research-oriented solutions. Evaluation criteria are proposed for assessing these systems, namely security and privacy, cost, performance, robustness, complexity, user preferences, commercial availability, and limitations. We compare the existing IPSs and outline the trade-offs among these systems from the viewpoint of a user in a PN.**

***Index Terms*—Personal Networks, Indoor Positioning Systems, Location Techniques.**

I. Introduction

ACCURATE, reliable and real-time indoor positioning and position-based protocols and services are required in the future generation of communications networks [1], [2], [3]. A positioning system enables a mobile device to determine its position, and makes the position of the device available for position-based services such as navigating, tracking or monitoring, etc. Location information of devices or users could significantly improve the performance of wireless network for network planning [4], network adaptation [5], load balancing [6], etc. Some position-based indoor tracking systems have been used in hospitals, where expensive equipment needs to be tracked to avoid being stolen, and the patients can get guidance to efficiently use the limited medical resources inside complex environments of the hospitals. Indoor navigation systems are also needed in a large public area to provide position indications for the users. For example, tourists need indoor navigation services in some large museums to see the artifacts in different places in sequence. In addition, position information brings benefits to self-organization and self-formation of ad hoc networks in the future communications systems.

The needs of users are highly addressed by the rapid development of integrated networks and services in personal networks (PNs) [7]. Much more attention has been paid to context-aware intelligent services for personal use, which make the persons' behaviors more convenient and simple. Position information in indoor environments is of course an essential part of the contexts. The uncertainty in dynamic and changing indoor environments is reduced by the availability of position information. And valuable position-based applications and services for users in PNs are enabled by location context offered by IPSs in various places such as homes, offices, sports centers, etc.

Global positioning system (GPS) [8] is the most widely used satellite-based positioning system, which offers maximum coverage. GPS capability can be added to various devices by adding GPS cards and accessories in these devices, which enable location-based services, such as navigation, tourism, etc. However, GPS can not be deployed for indoor use, because line-of-sight transmission between receivers and satellites is not possible in an indoor environment. Comparing with outdoor, indoor environments are more complex. There are various obstacles, for example, walls, equipment, human beings, influencing the propagation of electromagnetic waves, which lead to multi-path effects. Some interference and noise sources from other wired and wireless networks degrade the accuracy of positioning. The building geometry, the mobility of people and the atmospheric conditions result in multi-path and environmental effects [9]. Considering these issues, IPSs for indoor applications raise new challenges for the future communications systems.

Some articles [1], [10], [11] have given an overview of various available technology options for the design of an IPS such as infrared (IR), ultrasound, radio-frequency identification (RFID), wireless local area network (WLAN), Bluetooth, sensor networks, ultra-wideband (UWB), magnetic signals, vision analysis and audible sound. Based on these fundamental technologies, numerous IPSs have been developed by different companies, research centers and universities. Each system takes advantage of a particular positioning technology or combining some of these technologies, which also inherits the limitations of these technologies. The designers make trade-off between the overall performance and the complexity of the IPSs. In this paper, we systematically introduce and explain various commercially available and research-oriented IPSs. We also discuss the advantages and disadvantages of these IPSs and compare them in terms of the services design for the users in PNs.

The remainder of this paper is organized as follows. An overview of indoor positioning systems is presented in Section II. In Section III, we describe 17 existing IPSs and classify them into 6 categories according to their main medium used to sense location. The advantages and disadvantages of each

Manuscript received 14 May 2007; revised 1 February 2008.
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Digital Object Identifier 10.1109/SURV.2009.090103.

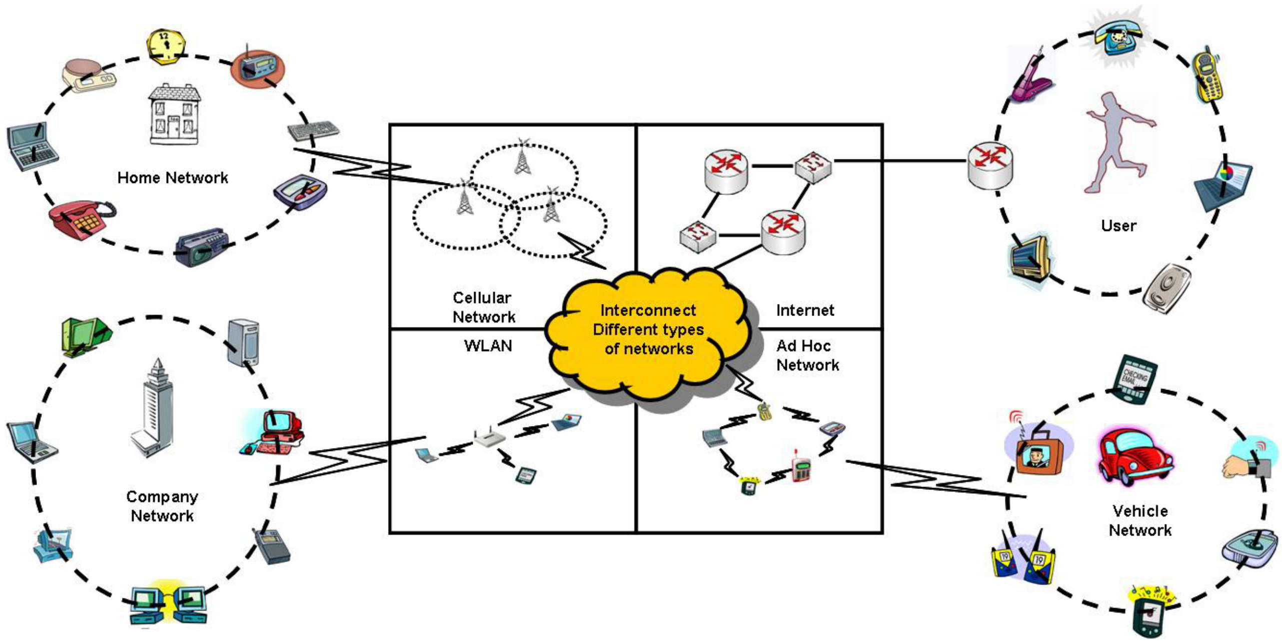


Fig. 1. Personal Network

of the IPSs are also included. Section IV evaluates each of the IPSs from the viewpoint of PNs. Finally, Section V summarizes our work and presents recommendations for future work.

II. An Overview of Indoor Positioning System for Personal Networks

In this section we describe and explain IPSs and personal networks. We address why PNs need position information. The existing IPSs are classified. Various evaluation criteria are proposed to compare them for the services demanded by the users in PNs.

A. What is a Personal Network?

To meet the demands of users, personal networks (PNs) [7], interconnect various users' personal devices at different places such as home, office, vehicle, etc., into one single network, which is transparent to the users, as shown in Figure 1. Through PNs, users can have global access to public and personal services in different types of networks with their personal devices. Personal devices may be equipped with different cellular and wireless networking technologies including wireless personal area network (WPAN), WLAN and the third-generation (3G) cellular networks. PNs connect personal devices with different networking technologies and form dynamic, private and secure networks. Thus PNs with the user-centric perspectives can facilitate personal ubiquitous communications anywhere and at anytime.

The success of PNs is highly dependent on the optimal organization of the personal devices to achieve efficient communication over various types of communications networks. Using different networking technologies, personal devices in each place form a personal area network (PAN), a vehicle area network, a home area network, a company area network, etc. Personal devices in the same or different places should cooperate with each other to form one single network for the user. Thus interconnecting numerous types of networks enables personal devices in these networks to communicate with each other and offer flexible personal services.

B. Why does a PN require an Indoor Positioning System?

In order to meet the user's needs and offer adaptive and convenient personal services, the location information of the persons and their devices at different places such as home, office, etc., can be provided by the IPSs to any applications in PNs. Although the GPS system can provide location information for users in outdoor environments, GPS can not give accurate positioning estimations for indoor use. Thus, IPS is required to support location-based services when the PN is located in indoor area. The need of IPS in PN is further illustrated by two typical scenarios, namely fitness center and conference. These scenarios are selected from a set of scenarios envisioned by the Information Societies and Technologies (IST) MAGNET Beyond project [15].

1) Fitness Center Scenario: Many people are keen to keep a healthy lifestyle by working out in a fitness center. A person named John is in his early 20's and would like to exercise for the purpose of losing weight. He has thus been a member of the local fitness center for the past two years. Today is one of his two weekly exercising days. As John enters the fitness room, his personal mobile device estimates his location that he is in the fitness center, which enables location-based services to provide the information of all network-enabled fitness equipment and displays this to John. Before commencing his fitness program, he needs to be weighed in order to track physical changes (i.e., weight loss) over time. He steps onto a scale capable of communicating with his mobile device. Based on the location context that he is on the scale, the personal service can communicate with the scale to get the measured weight and save it in his personal database for further comparison and exercising guidance. John can use various equipment in the fitness center. When he uses any equipment, John.s location information is required by the personal service to offer an adaptive personal training guide. For example, John steps on the threadmill, then the personal service automatically detects the position of John and monitors his heart rate during running. If his heart rate is too fast, which means John can not afford the running speed, the service will inform the threadmill to decrease the speed.

2) Conference Scenario: The conference is a typical scenario, which needs location information to offer flexible services for the users. For example, a journalist named Lily is visiting a technical conference. As she enters the event area, the local services can get her location information. Based on the location context information that she is in the service range of the local services, the services communicate with the devices carried by Lily and offer service-related information. Lily's devices receive the service-related information so that she can use various types of services provided by the conference. Using IPSs, an indoor navigation service can be provided to Lily to find the right presentation room in a conference hall. Her devices can be monitored and tracked by the positioning system to avoid them being stolen by other people. Furthermore, the temporary wireless network is self-organized based on the location information of the devices of the user to offer convenient and secure personal services. For example, Lily has the right of using the printing services in the conference, if her PN is formed and connected with the conference network so that a document in her laptop can be printed by a printer provided by the conference organizers.

Through the use cases, the location context awareness should be implemented in PN services, which offers comfort and efficiency to the end-user. However, IPSs enable location-based services and applications in PNs, which also raise significant security and privacy risks [16]. For example, in the fitness center scenario, when the user is out of the fitness center, he or she does not want the services to track him or her any more. So the location-aware services are required to ensure users' privacy.

C. What is an Indoor Positioning System?

An indoor positioning system (IPS) considers only indoor environments such as inside a building. The location of users or their devices in PNs can be determined by an IPS by measuring the location of their mobile devices in an indoor environment. Dempsey [13] defines an IPS as a system that continuously and in real-time can determine the position of something or someone in a physical space such as in a hospital, a gymnasium, a school, etc. [1]. From this definition, an IPS should work all the time unless the user turns off the system, offer updated position information of the target, estimate positions within a maximum time delay, and cover the expected area the users require to use an IPS.

An IPS can provide different kinds of location information for location-based applications required by the users. The *absolute location information* is provided by some IPSs. Before the position can be estimated, the map of the locating area such as an office, a floor, a building, etc., should be available and saved in the IPS. With respect to the map, the absolute position of a target can be measured and displayed. Usually, the absolute position information with respect to the map of a coverage area is offered by indoor positioning tracking systems and indoor navigation systems, because tracking and guiding services need the exact positions of the targets. The relative position information is another kind of outputs offered by the IPSs, which measure the motion of different parts of a target. For example, an IPS which tracks whether the door of a car is closed or not, needs to give the relative position information of the tracked point on the door with respect to the body of the car. The third kind of position information is proximity location information, which specifies the place where a target is. Sometimes, IPSs do not need to provide absolute or relative position information. The position monitoring and tracking systems in hospitals are such examples. The IPS should provide the room where a patient is. Thus location-based applications in hospital can monitor whether the patient enters a correct room for diagnoses or operations.

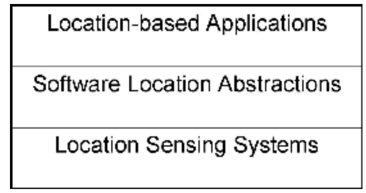


Fig. 2. Location-aware Computing System Architecture

The success of IPSs is starting to enable the location-aware computing systems in indoor situations. The system architecture of the location-aware computing systems [17] is illustrated in the Figure 2, which includes 3 layers, the location sensing systems, the software location abstractions and the location-based applications. At the location sensing systems layer, different location sensing technologies are used to perform measurements of the location of the users and their devices. The software location abstractions layer converts the data reported from the location sensing systems layer into a required presentation of the locations [18]. An example of the software location abstractions layer is the Java location application programming interface (API) [19]. The Java location API can produce the location information of targets in a standard format and provide access to a database of landmarks. Thus the developers can use this Java location API to develop location-based applications for resource limited devices. Moreover, the location-based applications, such as navigation and geographical advertising [20], are implemented at the highest layer, which use the location context information measured and calculated by the lower layers.

D. Location Technologies, Location Techniques and Location Algorithms

As the need of IPS is to enable location-awareness in computing systems, a number of wireless technologies have been developed for indoor location sensing. These technolo-

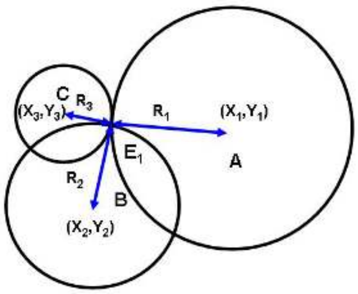
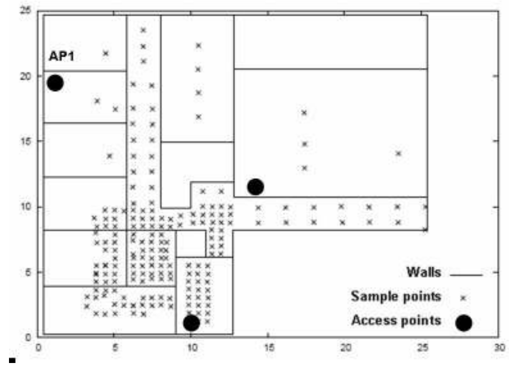
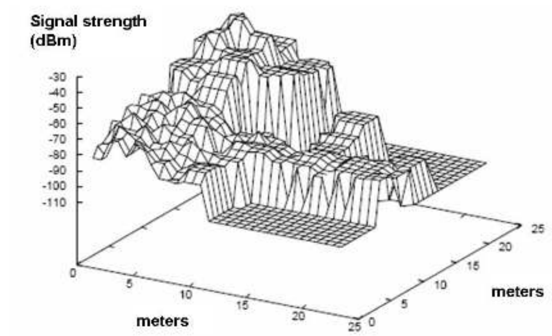


Fig. 3. Triangulation Positioning Techniques



(a) The Experiment Environment



(b) Signal Strength for AP1

Fig. 4. Fingerprinting Positioning Techniques [23]

gies include IR, ultra-sound, RFID, WLAN, Bluetooth, UWB, magnetic technology, etc. Each technology has unique advantages in performing location sensing for indoor use. For example, an IPS using WLAN technology does not need new infrastructures, because it can reuse the devices equipped with WLAN technology, which are widely deployed. At the same time, they have some limitations because of their properties. Various IPSs using one or combining two of these wireless technologies will be presented in detail in the following sections. And the influence of the wireless technologies on the performance of these IPSs will be discussed.

Equipped with one or several location technologies, IPSs use location techniques to locate objects and offer absolute, relative and proximity location information. There are four techniques for indoor position estimations: triangulation, fingerprinting, proximity and vision analysis [10], [50]. Triangulation, fingerprinting and vision analysis positioning techniques can provide absolute, relative and proximity position information. The proximity positioning technique can only offer proximity position information. In the design of IPSs, some IPSs use one positioning technique; others combine some of these positioning techniques to compensate for the limitations of single positioning technique.

Based on the geometric properties of triangles, three methods can be used to calculate the position, namely received signal strength (RSS), angle of arrival (AOA) and time of arrival (TOA) [1]. The basic principle of triangulation method for a 2-D position measurement is demonstrated in Figure 3. If the geographical coordinates (x_i, y_i) of three reference elements A, B, C are known, the absolute position E_1 can be calculated by using either the length [10] or the directions [10] of R_1, R_2 and R_3. Based on the information of the coverage area of an IPS, absolute, relative and proximity position information can be provided by the IPS using the triangulation method. Each triangulation method has advantages and limitations. TOA is the most accurate technique, which can filter out multi-path effects in the indoor situations. However, it is complex to implement [10]. RSS and TOA need to know the position of at least three reference elements, such as A, B, C in Figure 3, to estimate the position of an object. AOA only requires two position measuring elements to perform location estimation. However, when the target object to be located is far away, the AOA method may contain some errors, which will result in lower accuracy [21].

Fingerprinting positioning technique is proposed to improve the accuracy of indoor position measurements by using pre-measured location related data. Fingerprinting includes two phases: offline training phase and online position determination phase [50]. In the offline phase, useful location related data with respect to different places in the position estimation area is measured and collected for the position estimation. During the online position determination phase, the location related data of a target object is measured and compared with the pre-measured data collected in the offline phase to get a similar case in the database to make the location estimations. For example, in an IPS [23], WLAN technology is used in the position estimation. In Figure 4 (a), three access points (APs) are fixed in the different places in an area of 25 m x 25 m. In the offline phase, a laptop equipped with a WLAN card was moved to various sample points to measure the strength of the signals received from different APs, as shown in Figure 4 (a). These pre-measured signal strength values are used to make the fingerprinting maps of the area with respect to different APs. Figure 4 (b) shows the received signal strength from AP1 with respect to various sample points in the IPS working area. In the online position determination phase, based on the fingerprinting maps of the area, the IPS [23] uses the k-nearest-neighbours location algorithm [22] to locate the target node.

The proximity location sensing technique examines the location of a target object with respect to a known position or an area. The proximity location technique needs to fix a number of detectors at the known positions. When a tracked target is detected by a detector, the position of the target is considered to be in the proximity area marked by the detector.

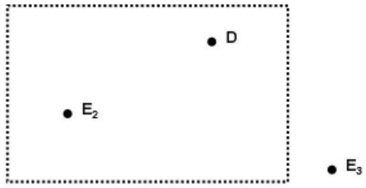


Fig. 5. Proximity Positioning Technique

As shown in the Figure 5, E_2 and E_3 are the tracked targets. A proximity area of the detector D is specified and shown by the dotted square in the Figure 5. E_2 and E_3 are located by monitoring whether they are in the proximity area or not. Thus the target E_2 is in the area of D and E_3 is not. Thus the proximity location sensing technique can not give absolute or relative position estimations as with the other three positioning techniques. The proximity location information provided is useful for various location-based services and applications. For example, a sensing area of a location measuring element is a room. Thus proximity sensing can accurately specify whether a tracked target is in the room or not.

The vision analysis estimates a location from the image received by one or multiple points [10] as shown in Figure 6. Vision positioning [84]-[87] brings the comfort and efficiency to the users, since no extra tracked devices are needed to be carried by the tracked persons. Usually, one or multiple cameras are fixed in the tracking area of an IPS to cover the whole place and take real-time images. From the images, the tracked targets are identified. The observed images of the targets are looked up in the pre-measured database to make the position estimations. In addition, vision positioning technique can provide useful location context for services based on the captured images. For example, in Figure 6, the vision positioning technique can observe that the girl is sitting on her sofa and using her laptop.

The location algorithms are specifically designed to specify how to calculate the position of a target object. For example, in the triangulation technique, when the distance between a target object and each reference point is obtained, the location algorithm calculates the location of the object. Researchers have developed various location algorithms to improve the accuracy of location calculation. The accuracy of the location information depends on whether the location data, such as the distance between a target object and each reference point, contains errors or not. If the initial location data includes a mix of correct and erroneous data, a priori knowledge of an IPSs behaviors and the properties of the coverage area are needed to improve the accuracy.

E. How to Classify Indoor Positioing System?

The IPSs can be categorized according to different criteria. One way to classify them is based on whether an IPS uses an existing wireless network infrastructure to measure the position of an object. The IPSs can be grouped as network-based approach and non-network-based approach. The network-based approach takes advantage of the existing network infrastructure, where no additional hardware infrastructure is needed. For cost reasons, the network-based approach

Fig. 6. An Example of Image used in Vision Positioning Technique

is preferred. However the non-network-based approach uses dedicated infrastructure for positioning and has the freedom of physical specifications by the designers, which may offer higher accuracy.

Another way of classifying IPSs is on the system architecture. There are three kinds: self-positioning architecture, infrastructure positioning architecture and self-oriented infrastructure-assisted architecture. Self-positioning calculates the positions by the targets themselves and takes advantage of the infrastructures of positioning systems, which provide high security and privacy. The infrastructure positioning estimates the positions of the targets using the infrastructures, which can automatically track the position of devices if they are in the coverage positioning area. In the self-oriented and infrastructure-assisted architecture, a tracked target sends a request to the positioning system to start the position measurements, and then gets its location information from the system. The key point of the third architecture is that unless the device allows a positioning system to track it, no positioning activities for the device can be carried out.

In this article, we classify the IPSs based on the main medium used to determine location, which include six categories: IR signals, ultrasound waves, radio frequency, electromagnetic waves, vision-based analysis and audible sound. In Section III, we will explain and compare the advantages and disadvantages of these media used in indoor positioning. And numerous IPSs in each category will be introduced.

F. What are the Criteria of Evaluating Indoor Positioning Systems for PNs?

To evaluate the IPSs for PNs, various important system performance and deployment criteria are proposed and described in this section. These criteria are proposed fully focusing on user preference and experience, and are used to evaluate if IPSs can meet the need of users in PNs.

1) Security and Privacy: Security and privacy [24]-[28] are important issues for IPSs in PNs, because PNs focus on the needs of users. private and social activities, who want to have full control of the usability of their personal location information and history. The user cares if someone tracks him/her and gets his/her history of all past activities. Controlling access to the location information [29] and distribution of the information [11] can improve the privacy in IPSs. The enhancements of security and privacy could be carried out from the software side and system architecture side [23]. For example, self-localized position system architecture [11] can ensure the privacy by performing location estimations in the target device. Unless the target device gives its location information to an entity, no one can access the information. Thus IPSs with self-localized location computation architecture can offer a high degree of security and privacy for the users in PNs.

2) Cost: The cost of an IPS contains several parts: the cost of the infrastructure components, the cost of a positioning device for each user and the cost of system installation and maintenance. Some positioning systems, such as GPS, have a large infrastructure to support the location measurement, which is expensive and complex. Some IPSs reuse the existing infrastructures such as WLAN, are more cost-effective, because there is no extra cost incurred by the infrastructure of IPSs. The cost of every positioning device at the user's side contains the device and maintenance cost, which are important for an individual person. Often, the device cost is specified when a person buys the device and starts to use the service of an IPS. But the users do not consider much about the device maintenance cost such as the battery cost and life time. For example, a device with longer battery life time needs less frequency of changing the batteries and lower maintenance cost. Positioning devices with self-positioning calculation ability are preferred to offer privacy of the end users, which raise the price of the devices and decrease the battery life time duration, because the devices are responsible for more complex positioning calculations. In addition, the cost of a positioning system installation and maintenance needs to be addressed for the long-term use of the system. Some IPSs include extra infrastructure to be installed such as sensor-based positioning systems, which need complex and expensive installations of fixing various sensors in different places in indoor situations. And some IPSs need professional engineers to support the operation of the IPS, which brings the cost of system maintenance higher.

The cost of the system can be addressed in different ways. Time and space costs are also factors indicating the efforts for the operation of an IPS. The time cost involves the time requirements of system installation and the time length of the positioning system in case of the system fails to work because of some serious faults. Space cost contains requirements of the size and the place, where the installed infrastructure components and user devices occupy. A large positioning device is not convenient for a user to carry it in his/her daily lives.

3) Performance: The accuracy and precision are two main performance parameters to evaluate an IPS, where the accuracy means the average error distance, and the precision is defined as the success probability of position estimations with respect to predefined accuracy. Moreover, the delay of an IPS is another performance aspect, which contains the delay of measuring, calculating positions of estimated target and forwarding position information to the requesting parts. There are two reasons: one is that the tracked target may move quickly; another one is that indoor environments are also dynamically changing. Scalability, defined as the number of objects that an IPSs can locate with a certain amount of infrastructure devices and within a given time period, is another issue of the performance evaluations for IPSs. A stable IPS, which can simultaneously locate a large number of objects, is preferred. For example, the orientation calculation of an object is required in a motion tracking application, which needs at least three, non-collinear, located targets mounted on the object to perform orientation calculation. Thus the deployed IPS needs to simultaneously locate, at least, three targets and offers higher scalability for the location sensing and location-based applications.

The performance of an IPS should be evaluated in order to examine whether it meets the requirements of the location-based services and applications in PNs or not. For example, an application for PNs in the home only needs room level accuracy. So the positioning system should offer the information, in which room person A is. Some indoor spaces cover only one floor, but others may have multiple floors. A positioning system offering 2-D position estimations can not meet the requirements of giving specifications of which floor the target is. Depending on the needs of users, 3-D positioning systems are preferred in some cases.

Usually, there is a trade-off between the price and the performance of an IPS. A system has higher performance also has higher cost. For example, the accuracy of an IR positioning system can be improved by adding filters to reduce the influence from florescent light and sunlight. However, the price of the whole system is increased because of these extra filters [11].

4) Robustness and Fault Tolerance: A robust IPS should be able to keep on operation even in some serious cases such as some devices in the system are malfunctioned, or a mobile device runs out of battery energy. For example, the IR positioning technique needs line-of-sight signal transmission between the emitters and the tags. In the Active Badge system [11], a user wears an active badge. If the badge is covered by his/her thick clothes, it can not get location information from the system, since the line-of-sight communications are not possible between the active badge and the emitters. Thus for these serious situations and faults in the system, the positioning system should still offer positioning services. In a sensor-based positioning system, if some sensors in a public area are stolen, the positioning system should still provide position information, which may have a lower accuracy, because the number of sensors in the measurement is reduced. In addition, the services and applications design for PNs needs to consider the situation that the location information of users and devices are not available, and the location related components do not stop functioning and can work in another way to support the demands of the users.

5) Complexity: An aspect of the complexity of IPSs is about the human intervention/efforts during the deployment and maintenance of the IPS. For IPS deployment, a rapid set-up of a system is required with a low number of fixed infrastructure components and easily used software platform for the users. Another issue during the IPS deployment is to enable optimum performance, such as accuracy, in each part of the entire deployment space [30]. For example, the WLAN-based IPSs reuse the existing access points (APs) of WLAN as reference locations and positioning measuring units, which do not need much infrastructure installation. Proper signal coverage should be offered by an IPS to cover all the desirable area, so that the performance can be ensured over all the coverage area [30].

Another aspect of the complexity indicates the required computing time of the device carried by the user to determine his/her position. Because of the limited CPU processing and battery power of the mobile devices, an IPS uses positioning methodology with lower calculation complexity is desired.

Using positioning system in a large space requires the system to be scalable with the increasing size of working area. For example, a positioning system deployed in a large building having many floors should not contain a large number of infrastructure devices and need time-consuming installation and maintenance. If the number of tracked components is large, an IPS should have the ability of offering precise location measurements for these elements at the same time. In addition, the sensing rate of positioning systems should be enough for the fast moving devices in complex indoor environments.

6) User Preference: Since personal networks are defined and developed for the needs of users, the IPSs should consider the users' requirements of the tracked devices, infrastructures and software. For the comfort of the users, the devices should be wireless, small, light weight, lower power consumption and computational powerful to offer rapid, accurate and real-time positioning services. For example, in some IPSs, tags are taken by persons to track their positions. Thus these tags should be easily wearable and fulfil the requirements described above. In addition, the infrastructure components and software used by people should be easily learnt and user interface friendly.

7) Commercial Availability: Among the existing IPSs, some are commercially available, and others are research-oriented, which are not available in the market. For the commercially available products, we can buy their devices and deploy the positioning systems. The designers consider and address multiple aspects of an IPS to make it popular in the market. But most of the companies keep the working principles of their commercial IPSs as secrets due to the competition among companies. For the research-oriented positioning systems, we can know their design details clearly, which is valuable for the future improvement of IPSs.

8) Limitations: Although the proposed IPSs have achieved various valuable improvements, they still have some limitations due to the positioning technology and other issues in the systems. One of the fundamental limitations is the medium used in position sensing. For example, using WLAN technology in positioning systems leads to great interest in the design of IPSs, because the system can reuse the existing infrastructure of WLAN and reduce the cost of positioning services. However, the radio frequency based positioning has multi-path and reflection effects resulting in a relatively higher error range. Another kind of limitations is the scope provided by the positioning systems. For example, some positioning systems only cover a short range. For large areas, these systems are not scalable. Another example is that some positioning systems are designed for a small number of persons or devices simultaneously using the positioning estimation services, which can not afford a large number of targets. In addition, some potential limitations should be considered in the evaluation of the positioning systems. For instance, using a positioning system may influence the performance of other wireless communications systems.

III. Indoor Positioning Systems for Personal Networks

Many positioning systems have been developed over the years for indoor location estimations. We introduce a variety of IPSs in this section. The location technology and technique used in each IPS are addressed to give a scientific overview of the system. Since the evaluation of these IPSs is focusing on the need of users in PNs, these IPSs are explained according to the criteria and requirements as specified in the subsection II-F. Thus we can know the advantages and limitations of these IPSs from the view of users in PNs.

A. Infrared (IR) Positioning Systems

Infrared (IR) positioning systems [30]-[41] are the most common positioning systems, because IR technology is available on board of various wired and wireless devices, such as TV, printer, mobile phones, PDAs, etc. An IR-based positioning system, which offers absolute position estimations, needs line-of-sight communication between transmitters and receivers without interference from strong light sources [30]. Thus the coverage range per infrastructure device is limited within a room. In this section, we describe some IR-based IPSs.

Active Badge: The Active Badge system [32]-[35] is one of the first indoor badge positioning systems designed at AT&T Cambridge in 1990s, which covers the area inside a building and provides symbolic location information of each active badge such as the room where the active badge is. The Active Badge system uses diffuse IR technology to realize location sensing [32]. By estimating the location of the active badges taken along with the persons, the Active Badge system can locate persons in its coverage area. An active badge transmits a globally unique IR signal every 15 seconds [32]. In each located place such as a room, one or more sensors are fixed and detect the IR signal sent by an active badge. The position of an active badge can be specified by the information from these sensors, which are connected with wires and forwards the location information of the tracked active badges to a central server. Based on the location information, some location-aware applications can be designed. For example, a location tracking application for helping a telephone receptionist has been proposed in [32]. Using the measured location of the employees in the building, the application displays a table onto a PC, which contains the names of these employees, their location (room numbers) and the nearest telephone. Thus, using the location information from the application, the user, a telephone receptionist, can forward the phone call to the expected employee.

Although the price of active badges and networked sensors are cheap, the cables connecting sensors raise the cost of the Active Badge system. The active badges taken by persons to locate themselves are light weight and have acceptable size. If the transmission frequency of an active badge is about every 15 seconds, the battery life time is half to one year, which is convenient for the users.

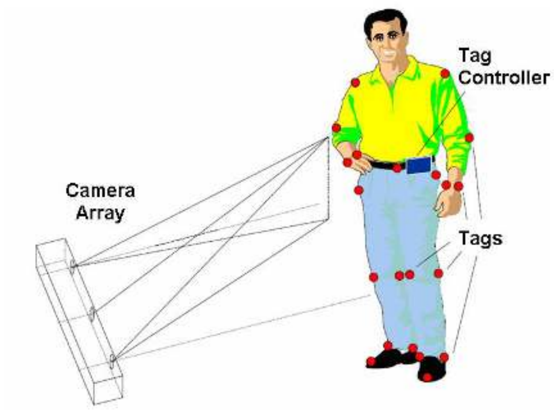


Fig. 7. Firefly Motion Tracking System Architecture [37]

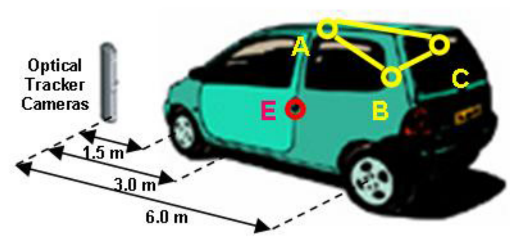


Fig. 8. OPTOTRAK PROseries System

The Active Badge system is an old project, which has been closed down. There is no commercial product of the system available. The system provides room level accuracy. However, the coverage range of IR signal is about several meters, positioning in a large room such as lecture room, needs more than one networked sensor to cover the whole area. An IR signal is influenced by fluorescent light and sunlight.

Firefly: Firefly designed by Cybernet System Corporation is an IR-based motion tracking system [36], [37]. The Firefly system uses IR tracking technology to offer high accuracy. The Firefly system animates complex motion of an object by locating the small tags emitting IR light and mounted on the object. The 3-D position information, which is generated by the system, can be used as an input to track the motion of moving objects. The position information can be used by virtual reality applications, such as computer games and computer animation. Since the Firefly system is a commercial product: its location techniques and algorithms are proprietary and have not been published, and so can not be described in this article.

As shown in Figure 7, the Firefly system contains a tag controller, tags and one camera array. The tag controller is carried by the tracked person, and it is a small, light weight (about 425 g) and battery-powered. Tags are IR emitters, which are supported by tag controller and mounted on different tracked parts of the person. Three cameras installed on a 1 m bar as a camera array receive the IR signals sent by tags fixed on different parts of the person.s body, and estimate the 3-D position of them. In addition, tags are much smaller than coins.

The Firefly system can offer a high level accuracy of about 3.0 mm. The position tracking is carried out in a high-speed and real-time way with measurement delay of 3 ms and sampling rate of 30 scans per second, if 30 tags are tracked. The system is easy to install and maintain. The cost of a Firefly system with a camera array, one tag controller and 32 tags is $27500.

Although the tag controller and the tags are small and portable, they are not comfortable to be worn in our daily lives, because they are connected using cables. The system can only operate correctly in a normal lighting environment. In addition, the coverage area is limited to within 7 m and the field of view is $40^\circ \times 40^\circ$. Thus the system is not suitable for the implementation in a large public area such as a shopping mall.

OPTOTRAK PROseries: OPTOTRAK PROseries [38] system is one of the IPSs designed by Northern Digital Inc. for congested shops and workspaces. The OPTOTRAK system uses a system of three cameras as a linear array to track 3-D positions of numerous markers on an object. As shown in Figure 8, the optical tracker includes 3 cameras can cover a volume of 20 m^3, and a maximum distance between tracked targets and the tracker is about 6.0 m. The system is a type of active system, where markers mounted on different parts of a tracked object emits IR light that is detected by the camera to estimate the location of them. The triangulation technique is used in the positioning process to calculate the positions of IR light emitters in the space.

OPTOTRAK system takes advantage of dynamic referencing, which is used to automatically compensate the movement, to measure relative motion. There is an example of dynamic referencing in Figure 8, where three emitters A, B and C mounted on the surface of a car form a dynamic reference with static relative positions, and the tracked emitter E fixed on the car door can be measured with relative position changes with respect to the formed dynamic reference. Thus even if the car is slightly moving, opening the door of the car can be accurately measured.

The system can offer a high accuracy of 0.1 mm to 0.5 mm with 95% success probability [39]. The IR emitters used in the system are small and light-weight with a diameter of 16 mm and the weight is 6 g. The OPTOTRAK system still covers a limited area (20 m^3). A disadvantage of OPTOTAK system is the line-of-sight requirement between the objects and the tracking system. By using a large number of IR markers, this problem can be partly solved.

Infrared Indoor Scour Local Positioning System (IRIS_LPS): Infrared Indoor Scour Local Positioning System (IRIS_LPS) [40] is an optical IR local positioning system. Cheap stationary mounted stereo-cameras receive IR signals from a tag carried by a target object to measure the angle of arrival and calculate the location of the tag by triangulation technique. The IRIS_LPS was tested in a lecture hall covering an area of 15 m $\times$ 9 m. Two cameras with IR filter and 120° wide angle lenses are mounted on a rail with a distance of 20 cm, which are fixed on the wall at a height of 3 m. And the cameras are connected to a computer, which extracts and processes the data to estimate the position of an object. In this situation, the system can offer accuracy of about 16 cm covering 100 m^2, which is larger than the covered areas of Firefly and Optotrak.

The system is cheap and easy to install and maintain. The system can support multiple tags being tracked at the same time. Although the IRIS_LPS can cover a larger area than Firefly and Optotrak, it results in less accurate position estimations, which shows a trade-off between accuracy and coverage area. This IPS can locate an object in a still mode with acceptable accuracy. For the moving object, the system needs to be improved to offer real-time motion tracking.

Summary of IR-based Positioning Systems: Using IR signal in the measurement of locations, the systems described in this section have some common advantages. The IR-based systems perform positioning estimations in a very accurate way. IR emitters are small, light-weight and easy to be carried by a person. The system architecture is simple, which does not need time-consuming installation and maintenance.

However, there are still some disadvantages with these indoor IR positioning systems. There are little considerations of security and privacy issues in the design of IR-based positioning systems. IR signals have some limitations for sensing location, for example, interference from florescent light and sunlight [31]. This problem can be solved by using optical and electronic filters to reject the disturbance from the light sources [41], and implementing noise cancelling signal processing algorithm at the receivers [31], which raise the cost of the positioning system. Another disadvantage is the expensive system hardware requirements. Although the IR emitters are cheap, the whole system using camera array and connected via wires is expensive comparing to the coverage area. There should be a transmitter or receiver in every measured place such as a room equipped with at least one IR device to locate whether the target persons or devices are in the room or not. These transmitters or receivers fixed in each place are connected using special wire. In addition, when an IR device taken by a person is covered by his/her clothes, the system fails to work since the IR wave can not penetrate opaque materials.

B. Ultra-sound Positioning Systems

Using ultrasound signal [42]-[48] is another way of position measurement. Ultrasound signals are used by bats to navigate in the night, which inspire people to design a similar navigating system in the last hundreds of years. In this section, several ultrasound positioning systems are introduced and their design principles and aims are addressed.

Active Bat: Active Bat positioning system [42] designed by researchers at AT&T Cambridge provides 3-D position and orientation information for the tracked tags. The Active Bat System uses ultrasonic technology and triangulation location technique to measure the location of a tag carried by a person. A tag periodically broadcasts a short pulse of ultrasound. The short pulse of ultrasound is received by a matrix of ceiling mounted receivers at known positions as shown in Figure 9. The distances between the tag and the receivers can be measured by the ultrasonic waves. TOA. Since all receivers are mounted on the ceiling, the tags are below the receiver matrix. The distance between a tag and three receivers is needed to calculate the 3-D position of the tag based on the principles of multilateration [43].

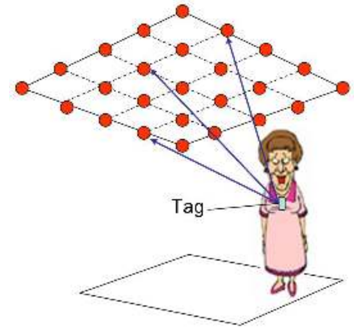


Fig. 9. Active Bat System

Tags are small and convenient tracked devices carried by persons with a volume of 7.5 cm × 3.5 cm × 1.5 cm. In the testing of the Active Bat system, the active tag is powered by a single 3.6 V Lithium Thionyl Chloride cell with a life time of around 15 months. So the users do not need to frequently change the batteries. 720 receivers are fixed on the ceiling to cover a 1000 m^2 floor, where 75 tags can be tracked with an accuracy of about 3 cm for 95% of the measurements. Each central controller can locate 3 tags at the same time with 50 times per second. In the maintenance phase, the battery voltage of each tag is monitored by the central controller, which is wired to all the receivers, to know the condition of the battery. Thus the battery voltage change does not influence the accuracy of position estimations.

However, the performance of this technology is influenced by the reflection and obstacles between tags and receivers, which degrades the system accuracy. From the view of a user, deploying a large number of sensors on the ceiling in each room is a time-consuming task, which degrades the scalability of this system. The receivers also need to be accurately placed, which results in complex and costly installation.

Cricket: Cricket system [44], [45] is a location system with the aim of offering user privacy, efficient performance and low cost. The cricket system uses TOA measuring method and triangulation location technique to locate a target. The cricket system includes ultrasound emitters as infrastructure attached on the walls or ceilings at known positions, and a receiver mounted on each object to be located. This approach provides privacy for the user by performing all the position triangulation calculation locally in the located object. Thus the located object owns its location information and can decide how and where to publish its location information. The emitters also transmit RF messages for synchronization of the TOA measurement and forwarding their location information in a decentralized fashion. Thus when there are not enough emitters for the triangulation location calculation, the receiver can use the semantic string forwarded by the radio link to get proximity location information.

The Cricket system addresses the issues of fault tolerance by using RF signals as a second method of proximity positioning in the case of not enough emitters available. Unlike the Active Bat system using a grid of receivers, the Cricket system uses less number of emitters fixed on the ceiling, because the target

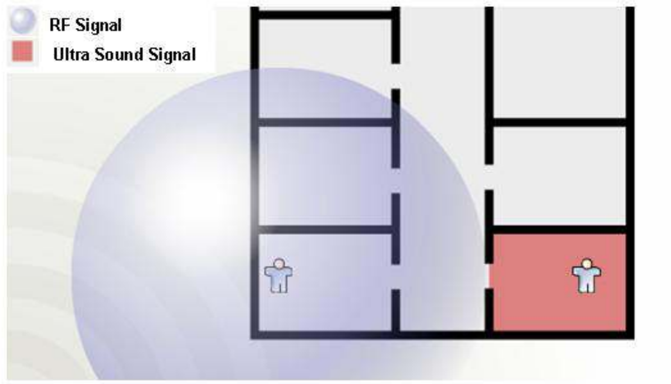


Fig. 10. Radio Frequency and Ultrasound Signal Comparison inside a building from a top view [46]

object receives and processes the ultrasound signals to locate itself. Thus the system is scalable for large area deployment inside a building. And the object receiver is cheap, about $10. So the cost of the whole system is low. Moreover, the Cricket system can provide a position estimation accuracy of 10 cm and an orientation accuracy of 3°. However, the located receivers in the system perform location estimations and receive both ultrasound and RF signal at the same time. Thus a receiver in the cricket system consumes more power, and its power supply needs to be designed in an efficient way to bring convenience to the users in stead of frequently changing batteries in the receiver.

Sonitor: The Sonitor ultrasound IPS [46] is an indoor tracking and positioning solution provided by Sonitor Technologies Inc. The Sonitor system can locate and track people and devices in real-time and offer proximity location information with room level accuracy. The ultrasound signals are suitable for room level location tracking. Comparing with the coverage range of a radio frequency signal as shown in Figure 10, the ultrasound signal can give a simple and accurate solution for room level positioning, because the ultrasound signals can not penetrate through the walls. Unlike Active Badge, the ultrasound technology does not need line-of-sight transmission between tracked targets and detectors as IR technology in the system. Thus the Sonitor system enables hidden targets to be tracked. For example, equipment in a drawer can be tracked by the Sonitor system, which is sometimes not possible by an IR positioning system.

In the Sonitor ultrasound IPS, tags attached to people or equipment are tracked by wireless detectors fixed in various rooms or places in an open public indoor area. A tracked tag transmits ultrasound signals with unique identification of each person or device. The transmitted ultrasound signals are received by a detector in the same room. The detector forwards this information through the existing wired or wireless LAN to a central positioning calculation and management element, which stores the tag's location and associated time. In addition, a Sonitor patented digital signal processing algorithm [46] is designed to protect the ultrasound signals from interference and help the detectors receive these signals successfully and correctly.

An energy-efficient method is proposed by the Sonitor ultrasound IPS, where the tags are activated by inside motion sensors, and transmit ultrasound signals in the case the tracked targets change locations. A sleeping mode is proposed by the designers to save power for the tags. Thus battery life time is extended, which can last up to 5 years with 600,000 transmissions. The size of each tag is 57.7 mm × 32.9 mm × 19.5 mm and the weight is 28 g, which is convenient for the users to carry. However, the Sonitor system can not give absolute position of a target. And the system needs numerous detectors fixed in each place of the tracking coverage area.

Summary of Ultrasound-based Positioning Systems: Ultrasound positioning systems give a kind of inexpensive positioning solutions. Usually the ultrasound signals used to locate objects need to be combined with RF signals, which perform synchronization and coordination in the system. These ultrasound positioning systems increase the system coverage area. However, ultrasound-based positioning systems have lower measurement accuracy (several centimeters) than IR-based systems (several millimeters). These ultrasound positioning systems suffer from reflected ultrasound signals and other noise sources such as jangling metal objects, crisp packets, etc.

C. Radio Frequency (RF) Positioning Systems

Radio frequency (RF) technologies [49], [50] are used in IPSs, which provide some advantages as follows. Radio waves can travel through walls and human bodies easier, thus the positioning system has a larger coverage area and needs less hardware comparing to other systems. RF-based positioning systems can reuse the existing RF technology systems such as APs in WLAN. Triangulation and fingerprinting techniques are widely used in RF-based positioning systems. For complicated indoor environments, location fingerprinting is an effective position estimation method, which uses location related characteristics such as RSS and location information of the transmitters to calculate the location of a user or a device.

1) Radio Frequency Identification (RFID): The radio frequency identification (RFID) is a means of storing and retrieving data through electromagnetic transmission to an RF compatible integrated circuit [51]. The RFID positioning systems are commonly used in complex indoor environments such as office, hospital, etc. RFID as a wireless technology enables flexible and cheap identification of individual person or device [52]. RFID technology can replace the identification technique such as the barcodes, and be used to design various products and services [53]. There are two kinds of RFID technologies, passive RFID and active RFID [51]-[53]. With passive RFID, a tracked tag is a receiver. Thus the tags with passive RFID are small and inexpensive. But the coverage range of tags is short. Active RFID tags are transceivers, which actively transmit their identification and other information. Thus the cost of tags is higher. On the other hand, the coverage area of active tags is larger. In this section, positioning systems [54]-[56] based on active RFID technology is explained in detail.

WhereNet: WhereNet positioning system [54], [55] is offered by Zebra Technology Company to provide various

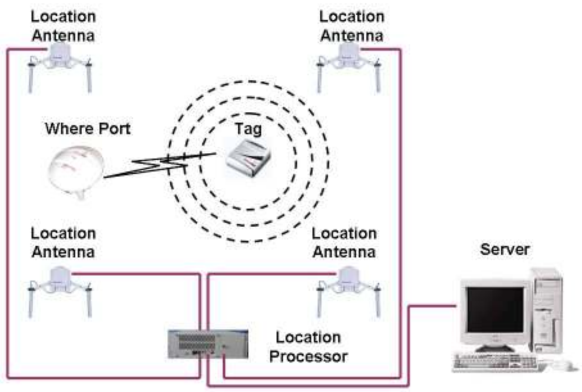


Fig. 11. WhereNet's Real Time Locating System

equipment to support indoor and outdoor real-time positioning. RFID technology is employed in WhereNet IPS to identify various located units, called tags, which can be mounted on the target located objects, such as a device or a person. WhereNet IPS uses sophisticated differential time of arrival (DTOA) algorithm [55] to calculate the locations of these tags. WhereNet IPS produces absolute location information of tags, which can be used by a number of location-based applications. For example, the Visibility Server Software, a location-based application, provides the visibility of the tracked tags and efficiently uses the location information from the WhereNet IPS.

WhereNet's Real Time Locating System (RTLS) [54], [55] consists of the following parts: tags, location antennas, location processors, servers, and Where Ports, which are shown in Figure 11. Tags are attached to their objects such as persons, devices, etc., so that it is possible to track location. In Figure 11, long range spread spectrum radio beacons are sent by tags with a unique identification number with respect to each tag to identify and locate them. Location antennas mounted on the ceiling at fixed positions receive signals from tags and forward the data to a location processor. The location processor uses the information from the location antennas to perform location calculation and can simultaneously track many tags. A location processor can connect with up to 8 location antennas via coaxial cable. Location processors transmit the calculated location information of tags to the server, where the location information can be saved and used by location-based services such as real-time tracking services. Where Ports fixed in different locations send low frequency electromagnetic signals to the tags to indicate the required behaviors of the tags based on the users' applications. For example, a Where Port offers specifications of the transmission frequency of the tags based on the location and the needs of the location-based services.

WhereNet tag III, which is a kind of tags [55] used in WhereNet IPS, is a small and convenient device for users. It has the size of 6.6 cm $\times$ 4.4 cm $\times$ 2.1 cm and the weight of 53 g. The tags are powered by batteries, which can last up to 7 years depending on the transmission rate of the tags. Based on the decision of the Where Ports, the transmission frequency of the tags is varying from every 5 seconds to one hour. However, the WhereNet offers an error range around 2 m to 3 m, which is not very accurate in indoor situations. The system is complex with numerous infrastructure components fixed in different locations. Thus the installation of these devices is time consuming.

Summary of RFID Positioning Systems: The RFID technology is not only for the indoor positioning applications, but also provides many potential services for the demands of users. The advantage of an RFID positioning system is light and small tags that can be taken by people to be tracked. The RFID system can uniquely identify equipment and persons tracked in the system. However, the proximity and absolute positioning techniques need numerous infrastructure components installed and maintained in the working area of an RFID positioning system.

2) WLAN: WLAN technology is very popular and has been implemented in public areas such as hospitals, train stations, universities, etc. WLAN-based positioning systems reuse the existing WLAN infrastructures in indoor environments, which lower the cost of indoor positioning. The accuracy of location estimations based on the signal strength of WLAN signals is affected by various elements in indoor environments such as movement and orientation of human body, the overlapping of APs, the nearby tracked mobile devices, walls, doors, etc. The influence of these sources and their impacts have been discussed and analyzed in the literature [57]-[61]. In this section, some WLAN-based IPSs are introduced and discussed.

RADAR: RADAR [57] positioning system was proposed by a Microsoft research group as an indoor position tracking system, which uses the existing WLAN technology. RADAR system employs signal strength and signal-to-noise ratio with the triangulation location technique. The multiple nearest neighbors in signal space (NNSS) location algorithm was proposed, which needs a location searching space constructed by a radio propagation model. The RADAR system can provide 2-D absolute position information and thereby enable location-based applications for users.

In the experiments of the RADAR system, 3 PCs are used as APs and one laptop is tracked as the target object. The system was tested on a floor inside a building, which is a typical indoor environment. The three APs measure the signal strength of the RF signals from the target. These measurements are used to calculate a 2-D position of the object. The system achieves an accuracy of about 4 m with about 50% probability.

The major advantages of RADAR system are that the existing indoor WLAN infrastructures are reused and it requires few base stations to perform location sensing. Thus the RADAR system is easy to be set up. However, the limitation is that the located object needs to be equipped with WLAN technology, which is difficult for some lightweight and energy-limited devices. There is also no consideration of privacy issues in the design of RADAR system, where a person using a device with WLAN interface may be tracked, even he/she does not want any one know his/her location. In addition, the RADAR system suffers from the limitations of RSS positioning methodology [50].

Ekahau: The Ekahau positioning system [58] uses the existing indoor WLAN infrastructures to continually monitor the motion of WiFi devices and tags. The triangulation

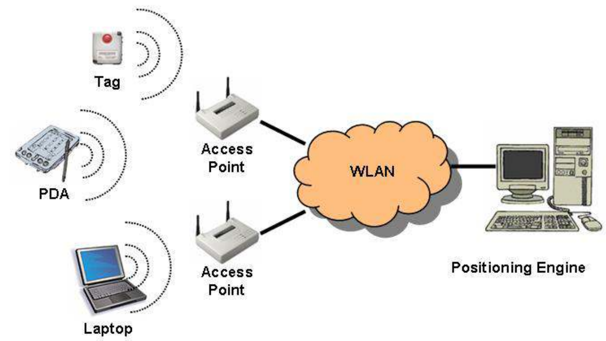


Fig. 12. System Architecture of Ekahau Positioning System

positioning techinique is used for locating any WiFi enabled device in Ekahau positioning system. The received signal strength indication (RSSI) values of the transmitted RF signals recorded at different APs are used to determine the targets. locations. The Ekahau positioning system offers 2-D location information, which can be used by location aware services and applications.

This solution is inexpensive and flexible to perform indoor positioning by tracking the tags with respect to reference devices, which are standard APs. The Ekahau system consists of three parts: site survey, WiFi location tags and positioning engines as shown in Figure 12. Site survey is a software tool, which provides site calibration before the real-time position estimations, and demonstrates the network coverage area, signal strength, SNR, data rate and overlapping of the WLAN network in users. social and professional places. The mapping of the network environment is quick with about 1,111 m^2 per hour. Another part is WiFi location tag, which can be attached to any tracked object to enable real-time positioning. The tags transmit RF signals. APs measure signal strength of the received RF signals. The measured data is forwarded via WLAN to the third part, which is a positioning engine, a software tool, offering real-time positioning to any device such as laptop, PDA, etc., using WLAN technology. Combining signal strength and site calibration done by site survey, the positioning engine calculates and displays the locations of WiFi location tags mounted on devices on the map of the local place.

The accuracy of the positioning system can achieve 1 m, if there are three or more overlapping APs that can be used to locate objects. The engine can simultaneously track thousands of devices. The Ekahau system achieves low cost by sharing the existing WLAN APs. The tags tracked are comfortable for the users to take them, with a size of 45 mm $\times$ 55 mm $\times$ 19 mm and weighing 48 g. The battery life time can last up to 5 years with low battery warning alerts to avoid the performance degradation because of the low power level of the battery. When the tags move, they start to work and be tracked, which offer an energy efficient solution and less influence to other WLAN-based communication.

COMPAS: The COMPASS system [61] takes advantages of WLAN infrastructures and digital compasses to provide low cost and relative high accurate positioning services to locate a user carrying a WLAN-enabled device. Position estimations are based on the signal strength measured by different APs. The COMPASS system uses fingerprinting location technique and a probabilistic positioning algorithm to determine the location of a user [61]. A major contribution of the COMPASS system is that the user's orientation is considered in the location sensing process. A user's orientation is measured by a digital compass to reduce the human body blocking influence to the positioning process. A digital compass is a low cost and low power consumption component with small size, because digital compass is integrated into a chip.

For the tracking of a mobile user, the orientation impact is highly addressed and analyzed in detail by the designers of both RADAR and COMPASS system. As human body contain more than 50% water, which absorbs the 2.4 GHz radio signal, the clocking effect of human body influences the measurement accuracy. COMPASS system aims at solving this problem by increasing the number of signal strength samples in each position with different orientations.

The test experiments were taken in an area of 312 m^2 on a floor inside a building. In this situation, the COMPASS system achieves an accuracy of about 1.65 m. But the RADAR system only has an error distance of 2.26 m in the same case. However, the COMPASS system only considers tracking a single user. Locating multiple users at the same time has not been discussed. Thus the scalability of the COMPASS system is low to provide location sensing for multiple targets.

Summary of WLAN-based Positioning Systems: IPSs have the goal of increasing the location estimation performance, and at the same time reducing the cost of system. WLAN-based indoor positioning [57]-[61] is an example of low cost positioning technology, which uses the existing infrastructures in indoor environments. WLAN technology is widely used and integrated in various wireless devices such as PDAs, laptops, mobile phones, etc. Thus the WLAN-based positioning systems can also reuse these wireless devices as tracked targets to locate persons. However, because of complex indoor environments consisting of various influenced sources [57]-[61], the performance of the positioning systems are not very accurate with an accuracy of several meters. And using the stored information and fingerprinting technique in the location estimations is complex and costly if the number of users of the positioning system is increasing significantly.

3) Bluetooth: Bluetooth, the IEEE 802.15.1 standard, is a specification for WPAN. Bluetooth enables a range of 100 m (Bluetooth 2.0 Standards) communication to replace the IR ports mounted on mobile devices. Piconets are formed under Bluetooth specifications by using a master/slave based MAC protocol. Bluetooth technology has been implanted in various types of devices such as mobile phone, laptop, desktop, PDA, etc. In addition, Bluetooth chipsets are low cost, which results in low price tracked tags used in the positioning systems.

In Bluetooth-based positioning systems [62]- [73], various Bluetooth clusters are formed as infrastructures for positioning. The position of a Bluetooth mobile device is located by the effort of other mobile terminals in the same cluster. In this section, a Bluetooth-based IPS is introduced.

Topaz: The Topaz location system [74] uses Bluetooth technology to locate tags in indoor environments. By using Bluetooth technology, Topaz can only provide 2-D location

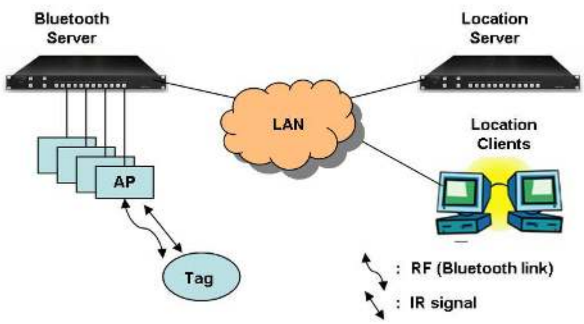


Fig. 13. The System Architecture of Topaz IPS

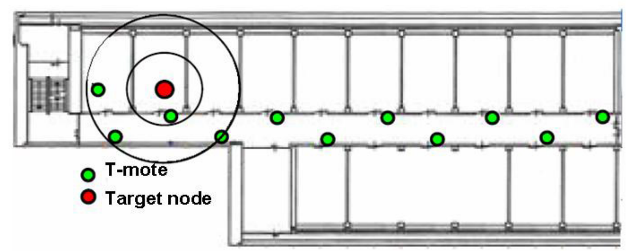


Fig. 14. System overview of evaluation of OPT on a floor

information with an error range of around 2 m, which is not sufficient to provide room level accuracy in a multi-obstacle indoor environment. Thus the Topaz system combines the Bluetooth-based positioning with IR-based positioning technique, where IR location techonology is suitable for this aim. IR can not penetrate the walls of the rooms, which offer perfect room level accuracy. The Topaz location system consists of software and hardware parts for local positioning of Bluetooth tags or any device equipped with Bluetooth technology.

Figure 13 shows the system components and the architecture of Topaz indoor location system. In the system, tags are located by numerous Bluetooth and IR enabled APs fixed in different places. Typically, 32 APs are associated with one Bluetooth server, which is responsible for performing Bluetooth functionalities such as managing APs. The Bluetooth servers receive the measured signal strength and forward the raw data to the Location server. The location server calculates the location of the tags. Bluetooth servers, location servers and location clients are connected with LAN.

Combining Bluetooth technology and IR technology, the target device can be located in the correct room. Tens of objects can be tracked at the same time. However, the tags using batteries need to be charged once per week, which is a short period compared with tags used in other positioning systems. The delay of calculating the position of a tag is quite long, around 10 s to 30 s.

Summary of Bluetooth-based Positioing System: Using Bluetooth technology in location sensing can reuse the devices already equipped with Bluetooth technology. Since Bluetooth is a low-cost and low-power technology, it is an efficient way to design IPSs using Bluetooth. However, a disadvantage of Bluetooth-based positioning system is that the syatem can only provide accuracy from 2 m to 3 m with the delay of about 20 s. The Bluetooth positioning systems suffer from the drawbacks of RF positioning technique in the complex and changing indoor situations [62].

4) Sensor Networks: Sensors are devices exposed to a physical or environmental condition including sound, pressure, temperature, light, etc., and generate proportional outputs. Sensors are typically divided into two kinds: active sensors and passive sensors. Active sensors can interact with the environment such as radars. Passive sensors only receive information from the outside world. The sensor-based positioning systems consist of a large number of sensors fixed in predefined locations [75]. From the measurements taken by these sensors, a person or device can be located. Positioning methods using sensor networks were discussed in [76]. This section will introduce a sensor-based IPS.

Online Person Tracking (OPT) System: Online Person Tracking (OPT) system [77] is designed to provide location information to the context-aware applications in PNs. OPT is a low-cost positioning system with a number of sensors deployed at fixed positions in indoor environments. OPT uses cheap and small sensors called T-mote [78]. The sensors are employed and mounted at fixed positions in the OPT system. These sensors take advantages of RSSI to measure the distance between a transmitter sensor and a receiver sensor. Based on these determined distances, triangulation location technique with a weighted minimum mean square error (W-MMSE) location algorithm [77] is used.

A prototype was designed and implemented to test the performance of real-time person tracking in OPT system. The testing experiments were taken on a floor inside a building, which is shown in Figure 14. The triangulation method is used in the OPT system based on the RSSI value measured by 3 or more sensors. A target node carries a T-mote to be tracked by OPT system. Various T-motes receive the signal from the target node and measure the RSSI values of these signals. Then T-motes forward these data to a location-based application, which is software implemented in a laptop, through the wireless sensor network. The location application calculates the position of the target node, and displays its position on the floor map through GUI.

OPT system gives a low cost location sensing solution that reuses the sensors deployed at fixed positions in the indoor environments. However, the accuracy of the system varies from 1.5 m to 3.8 m, which is not very accurate to offer room level location information. And installing sensors in fixed locations and maintaining numerous sensors in OPT system is complex.

Summary of Sensor-based Positioning Systems: Sensor-based positioning [75]-[77] provides a cost effective and convenient way of locating persons and devices due to the decreasing of the price and the size of sensors. At the same time, cheap and small sensors have limited processing capability and battery power comparing to other wireless devices such as mobile phone, PDA, etc. Thus using sensor technology in indoor positioning has some drawbacks: less accuracy, the

Fig. 15. Hardware of the Ubisense System in a Academic Research Package: five tags (left) and four sensors (right)

Fig. 16. Components of MotionStar Wireless System: transmitter and controller (left), base station (right up), mounted sensors and RF transmitters (right down) [83]

limited battery power in the case of real-time tracking, lower computational ability, etc., which needs further improved to offer precise and flexible indoor positioning services.

5) UWB: The RF positioning systems suffer from the multi-path distortion of radio signals reflected by walls in indoor environments. The ultra-wideband (UWB) [79] pulses having a short duration (less than 1 ns) make it possible to filter the reflected signals from the original signal, which offer higher accuracy. Using UWB technology in positioning systems has been a popular way of improving the positioning accuracy [80]. In this section, a UWB-based positioning system is introduced.

Ubisense: The Ubisense Company, which is funded by engineers from AT&T Cambridge, provides a new real-time positioning system based on UWB technology [81]. The triangulation locating technique, which takes advantages of both the time difference of arrival (TDOA) and AOA techniques, is employed in the system to provide flexible capability of location sensing. Since Ubisense can measure signal angles and difference in arrival times, and complex indoor environments including walls and doors do not significantly influence the performance [81], the accuracy offered by Ubisense is about tens of centimeters.

The Ubisense system consists of three parts: the sensors, the tracked tags and the Ubisense software platform as shown in Figure 15. The active tags transmit UWB pulses. The sensors, which are fixed in the known locations, receive the UWB signals from the tracked tags. Then the location data of the tags is forwarded from these sensors via existing Ethernet to the Ubisense software platform, which analyses and displays the location of the tags. The software platform includes two parts: Location Engine and Location Platform. Location Engine is a run-time component and enables sensors and tags to be set up. Location Platform gathers location data from for location-aware applications. For example, one location-aware application is real-time monitoring and displaying the location the target tags according to the imported coverage area model. The visualization of the location of tags is provided, and absolute, relative and proximity location information can be abstracted and offered to various location-aware applications.

Comparing with the other RF-based positioning systems, the Ubisense system results in a higher accuracy of about 15 cm in 3-D. The time delay of the position estimations is short and the sensing rate can be up to 20 times per second. The Ubisense sensors are organized into cells. In each cell, there are at least four sensors, which cover an area of up to 400 m^2. Thus the coverage range per infrastructure element is large. The system is scalable with respect to a large position monitoring area. The tracked tags are wireless, easily wearable, and light weight (45 g) and a long battery life time of about 1 year. However, the price of this high performance positioning system is also high. An active research package as shown in Figure 15 costs about $16,875.

Summary of UWB-based Positioing Systems: UWB technology offers various advantages over other positioning technologies used in the IPSs: no line-of-sight requirement, no multi-path distortion, less interference, high penetration ability, etc. Thus using UWB technology provides a higher accuracy. Furthermore, the UWB sensors are cheap, which make the positioning system a cost-effective solution. In addition, the large coverage range of each sensor results in that the UWB-based positioning system is scalable.

D. Magnetic Positioning System

Using magnetic signals is an old and classic way of position measuring and tracking [82]. The magnetic positioning systems offer high accuracy and do not suffer from the line-of-sight problems, where the positions are measured in the case of an obstacle between the transmitters and receivers. This section introduces a magnetic positioning system in detail.

MotionStar Wireless: MotionStar Wireless [83] is a motion tracking system that uses pulsed DC magnetic fields to simultaneously locate sensors within 3 m coverage area. MotionStar Wireless is an improved version of the original wired motion tracking system named MotionStar designed by Ascension Technology Corporation. By modifying the design of the old version, MotionStar, there is no wire between a tracked person and a base station tracking the person's motion. MotionStar wireless system provides precise body motion tracking by measuring numerous sensors mounted on the different parts of a person. Thus the position information of sensors determined by the MotionStar Wireless system can be used by various applications, such as Animation, Biomechanics, virtual reality, etc.

The MotionStar wireless system tracks multiple targets (up to 120 sensors) at the same time and in real-time. The systems consist of a transmitter and controller, a base station, mounted sensors and RF transmitters, as illustrated in Figure 16. The transmitter and controller part sends magnetic pulses to the body mounted sensors. Then each sensor mounted on a particular body part receives magnetic pulses from the transmitter and controller. The sensors are connected through wires to the RF transmitter, which is carried by the tracked person. The RF transmitter can connect up to 20 sensors and transmits the measured data to the base station. Finally, the base station calculates the position and orientation of sensors and transfers the measured data to the user's computer through RS232 or Ethernet interface. These estimated data can be used for animation and tracking applications.

The error range of the static position estimating is about 1 cm. The update rate of the position measurements is up to 120 measurements per second. The sensors carried by a tracked person are small (2.54 cm $\times$ 2.54 cm $\times$ 2.03 cm) and light weight (21 g), which are highly portable and comfortable wearing devices. These mounted sensors are connected via wires with the back pack RF transmitter, which has the size of 17.5 cm $\times$ 14 cm $\times$ 4.54 cm and the weight of 0.99 kg. However, the disadvantage of the Motion Star system is that the magnetic trackers are quite expensive. The battery life time for continuous motion tracking is around 1 hour or 2 hours, which is a short period for daily position estimations. And the performance of the Motion Star system is influenced by the presence of metal elements in the positioning estimating area. In addition, the coverage range of each transmitter is limited within 3 m, which is not scalable for large indoor public applications and services.

Summary of Magnetic Positioning Systems: The magnetic sensors are small in size, robust and cheap, which bring benefits for positioning estimations in indoor environments. The magnetic-based positioning systems can offer higher accuracy and afford multi-position tracking at the same time. However, the limited coverage range is a drawback for the performance of the magnetic IPSs. Thus increasing the coverage range of each magnetic transceiver or using various magnetic infrastructures to cover enough area for indoor use needs further study, design and development.

E. Vision-based Positioning System

Vision-based positioning is a way of tracking the locations and identifying persons or devices in a complex indoor environment [84]-[86]. The vision-based positioning does not need the tracked person carrying or wearing any device. And vision can easily provide some location-based information such as person A is drinking wine and sitting on his/her sofa. In this section, an example of vision-based positioning system is explained, and the pros and cons of vision-based positioning are discussed.

Easy Living: Microsoft research group designed the Easy Living positioning system based on vision-based location techniques [87]. Vision-based location techniques can capture the motion of the targets with data from a single perspective or multiple perspectives. Easy Living systems use the multiple-perspective vision-based location technique with two cameras covering the whole measuring area. The location estimation in Easy Living system combines color and depth from the two cameras to provide position sensing and target identification services.

The components of the Easy Living system are demonstrated in Figure 17. In the evaluation of the Easy Living system, two stereo cameras are mounted on the ceiling of a room. Thus every part of the room is covered by at least one camera. Two real-time 3-D cameras are responsible for covering the measured area and providing updated visions, which are raw data to be used in the position estimations. To reduce the influence of changes in the background, depth and color pixels are used in the modeling of the background. Then PCs running the stereo module receive the images taken by the cameras and process these raw data. To identify each tracked person, Easy Living system defines a "person creation zone", which is normally near the entrance of the room. Thus, when a person enters the room, in this "person creation zone", the stereo module creates the vision instance of the person. Then the stereo model tracks the motion of the person and keeps the location history of the person. Using the saved location information of the person, the Easy Living system can correct some mistaken location estimations.

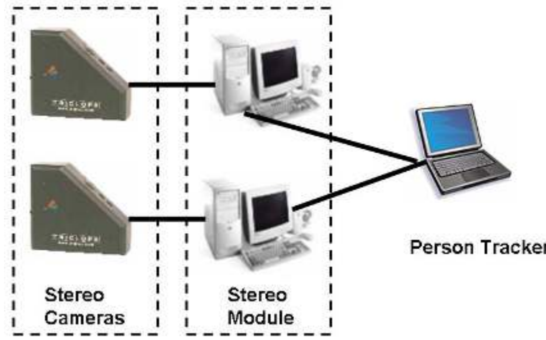


Fig. 17. Easy Living System Components [87]

Although Easy Living system is very convenient for the users, there are still some disadvantages of the system. The Easy Living system needs substantial processing power to process the images taken by the stereo cameras, because image processing is complex. And the system's accuracy can not be guaranteed due to the interference of dynamic changing environment to the vision data.

Summary of Vision-based Positioning Systems: In vision-based positioning systems, a low price camera can cover a large area. The users do not need to carry any location device, and can be located by the vision-based IPS. However, these systems still have some drawbacks. Firstly, the privacy of people is not provided by the vision-based positioning. Secondly, the system is not reliable in a dynamic changing environment. Since the position estimations are based on the saved vision information in a database, which needs to be updated due to the changing in the environment such as changing the place of your desk in your office. The vision-based positioning is influenced by many interference sources such as weather, light, etc. For example, the turning on and off a light in a room reduces the accuracy of tracking a person.s motion. In addition, tracking multiple persons moving round at the same is still a challenge for the vision-based positioning, which needs higher computational ability of the positioning system.

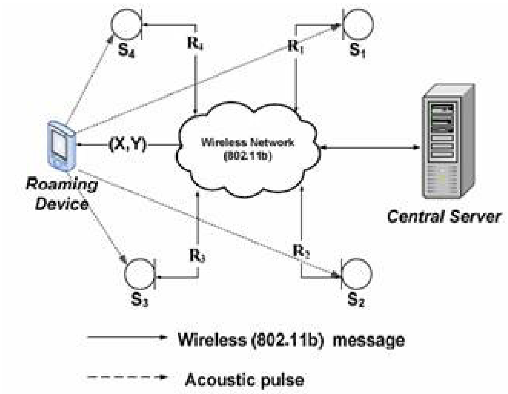


Fig. 18. System Architecture of Beep [90]

F. Audible Sound Positioning System

Audible sound is a possible technology for indoor positioning [88]. Nearly every mobile device has the ability of emitting audible sound such as mobile phone, PDA, etc. The audible sound-based positioning system can reuse these devices owned by the users for indoor positioning. Wearable tracked tags are no longer needed resulting in a low-cost system.

Beep: A 3-D IPS named Beep [89], [90] was designed as a cheap positioning solution using audible sound technology. Triangulation location technique is used in Beep with a standard 3-D multilateration algorithm based on TOA measured by the sensors in Beep system. The 3-D location information determined by Beep can be used by various practical applications as proposed by Beep in the situations, such as office building, shopping center, etc.

Figure 18 shows the architecture of the Beep positioning system. A roaming device is used as a tracked target in the system to send audible sound. Various acoustic sensors (S_i) are pre-installed at fixed positions in the measuring area and connected to the central server through wireless connection (R_i). These sensors receive the audible sound transmitted from the tracked device and forward these data to the central server through WLAN. TOA technology and triangulation method are used to estimate the position of the device. Finally, the roaming device can get its position information from the central server via WLAN. The testing experiments were taken in a 20 m $\times$ 9 m room. The positioning system can achieve up to an accuracy of 0.4 m with 90% of all cases. In addition, the effect of sound noise and obstacles reduce the positioning accuracy by 6-10%.

One of the benefits brought by the Beep system is that the privacy of the users is considered by avoiding them being tracked automatically. The users can stop their devices from sending audible sound; if they do not want the system knows their location.

Summary of Audible Sound Positioning Systems: Audible sound is an available service in various mobile devices used in our daily lives. Thus the users can use their personal devices in an audible sound positioning system to get their positions. Because of properties of audible sound, using it for indoor positioning has some limitations. The audible sound can be interfered by the sound noises in the dynamic changing and public indoor situations. Audible sound does not have high penetration ability, so the scope of an infrastructure component is within a single room. Transmitting audible sound is a kind of noise to indoor environments, where people would not like to hear audible sound made by the positioning services.

IV. Comparisons

In this section, the existing IPSs described in Section III are evaluated from the viewpoint of user needs in PNs. IPSs are compared with respect to various aspects as introduced in the section II-F, including security and privacy, cost, performance, robustness, complexity, user preference, availability, and limitations. These criteria are proposed based on the user need, preference and convenience. The evaluation and comparison results are shown in Table I and Table II. For each design requirement of PN, these IPSs are compared. Thus, in the future IPS design for PNs, we can use the comparisons in these tables to easily find the perfect location methods and system design issues with respect to each evaluation criteria to enable location-aware intelligence in PNs. For example, for the "Fitness Center Scenario" described in subsection II-B, an IPS can be chosen based on the eight evaluation criteria. From Table I and Table II, we can obtain the best IPS that fulfils the requirement of the IPS for "Fitness Center Scenario".

V. Conclusion

In the next generation communications networks, the telecommunications applications require various types of context information of the environments, persons and devices to offer flexible and adaptive services in PNs. Location context is a kind of context information, which enables location-aware intelligence to improve the quality of lives. A personal network focuses on the demands of a user to integrate all his/her personal devices at various places in different types of networks into one single network, which provides a private and user-centric solution. The IPSs produce absolute, relative and proximity location information for the users and their devices in indoor environments. Based on the measured location information, tracking, navigation, monitoring and other location-aware services can be designed for the users in PNs.

In this article, we describe the concept of IPSs and introduce the types of location data offered by IPSs. Typical scenarios and use cases are explained to show the requirements of location data in PNs. Then we classified 17 existing IPSs into 6 categories based on the main medium used to sense location. We explained the system architecture and working principles, and discussed the advantages and disadvantages of each IPS.

From this survey, we can see that each medium used in position estimations has its limitations. None of the technologies can satisfy the system requirements of performance and cost. Instead of using a single medium to estimate the locations of the targets, combining some positioning technologies can improve the quality of positioning services [91]. For example, the SVG system [92] combines the advantages of WLAN and UWB based positioning technologies, where WLAN technology can provide positioning services covering large area and UWB can give highly accurate position estimated in some small required areas.

TABLE I
SUMMARY AND COMPARISON OF IPSS IN SECURITY AND PRIVACY, COST, PERFORMANCE AND ROBUSTNESS

System Name	Security and Privacy	Cost	Performance	Robustness
Active Badge [32]-[35]	No	Resonable price with cheap tags and sensors	Room level accuracy	Line of sight requirements and influence from light source
Firefly [36], [37]	No	A tag controller and 32 tags cost $27,500	Error range below 3.0 mm; high positioning frequency; short delay	Influence from light source
OPTOTRAK [38]	No	Expensive	An accuracy of 0.1 mm to 0.5 mm with 95%	Line of sight requirement
IRIS_LPS [40]	No	Less than Firefly and OPTOTRAK	Error range is about 16 cm; IRIS_LPS is accurate than Firefly and OPTOTRAK	IRIS_LPS can only locate a static object with acceptable accuracy. For moving objects, the system need to be improved
Active Bat [42]	No	Expensive	The accuracy is about 3.0 cm with 95% probability	Influenced by reflection from and obstacles between a tag and a receiver
Cricket [44], [45]	Yes	Cheap	An accuracy of 10 cm and an orientation accuracy of 3°	Good
Sonitor [46]	No	Inexpensive	Room level accuracy	Hidden targets can be tracked
WhereNet [54], [55]	No	Not Cheap	Error range of 2 m to 3 m; position estimation frequency is every 5 seconds to 1 hour	Instead of using RFID technology in positioning magnetic signals are used to give the location zone of a tracked target
RADAR [57]	No	Research-oriented solution, no products	The accuracy is about 4 m with 50% probability	As the accuracy is low, the position measurement are not reliable
Ekahau [58]	No	Inexpensive	The accuracy is up to 1 m, and the system can simultaneously track thousands of devices	Only if there are enough APs (more than 3), the system can locate a target with an accuracy of up to 1 m
COMPASS [61]	No	Inexpensive	The accuracy is about 1.65 m	The system considers the human body blocking effect and use digital compasses to improve the performance
Topaz [74]	No	High	Error range is about 2 m to 3 m, room level accuracy	Using Bluetooth and IR technologies at the same time to achieve higher robustness
OPT [77]	No	Cheap	Error range is about 1.5 m to 3.8 m	The system needs at least three sensor measurements to locate target
Ubisense [81]	No	An active research package containing 5 tags and 4 sensors cost $18,354	The accuracy is about 15 cm with with short location estimation delay	Good
MotionStar [83]	No	Expensive magnetic trackers	The accuracy is about 1 cm; both the position and orientation are estimated	Influenced by metal elements
Easy Living [87]	No	Inexpensive stereo cameras are used	The system accuracy cannot be guaranteed due to various interference sources	The system is not reliable in a dyanmic changing environment
Beep [89], [90]	Yes	Inexpensive sensors	The accuracy is up to 0.4 cm with with 90% cases	Influenced by sound sources in the same place

Since people have certain habits in their daily lives and follow routines in their living and working environments, the position of users can be predicted based on the previous position information. Position prediction is described in [93], which supports efficient and cognitive applications for the users in PNs. Furthermore, the position prediction can be used together with other types of context information such as user preference, time, weather, etc., to consider multiple issues of a user and the situation in which the user is. Another future research issue is to consider the influence of mobility in IPSs, which includes the mobility of the located object and the mobility of people and equipment in indoor situations. The design of an IPS should ensure optimum performance for a moving target in a varying indoor situation. Thus the position measurements, position prediction and other related context will be used together to enhance the context-aware intelligence in PNs.

Taking location sensing technology and system design, some on-going research projects are trying to improve the performance of IPSs. A project named ”Development of Location Centric Networks” [94] is undertaken by Mitsubishi Electric Research Laboratories (MERL) to estimate the location of transceivers in an UWB impulse radio network. Currently, the location system proposed by this project can determine the location of an object with an accuracy of 15 centimetres and cover large area. Another on-going research project is ”Indoor position location technology project” [95] taken by the Commonwealth Scientific and Industrial Research Organization (CSIRO) in Australia. The aim of the project is to improve the accuracy of location estimation, at the same time, reduce the cost of indoor tracking systems. The third project is a ”Real-Time Location System (RTLS) Healthcare”, which is undertaken by AeroScout Company [96], an industry leader of WiFi-based active RFID solutions. The project focuses on patients care in digital hospitals to propose advanced locating technologies and methods.

From this survey, readers can have a comprehensive understanding of the existing IPSs, especially the 17 IPSs surveyed and discussed in this paper. Eight criteria, which include security and privacy, cost, performance, robustness,

TABLE II
SUMMARY AND COMPARISON OF IPSS IN COMPLEXITY, USER PREFERENCE, AVAILABILITY AND LIMITATIONS

System Name	Complexity	User Preference	Availability	Limitations
Active Badge [32]-[35]	Low	The active badges are lightweight and have acceptable size; the battery life is about half to one year	Not Available	Absolute location information is not available
Firefly [36], [37]	Low	Tag controller and tags are not comfortable to be worn, because they are wired	Commercially available	The scope of this system is limited within 7 m
OPTOTRAK [38]	Low	No battery; the emitters are small and wired connected to the power supply	Commercially available	Limited coverage area
IRIS_LPS [40]	Low	No battery; emitters are small	Not available	A trade-off between accuracy and coverage
Active Bat [42]	Lots of receivers need to be mounted on the ceiling	The battery life is about 15 months	Not available	Deploying large numbers of sensors on the ceiling for each room is a time-consuming task
Cricket [44], [45]	Low	The object receiver consumes more power, because the position calculation is done by itself	Not available	Mobile device's power consumption
Sonitor [46]	Numerous detectors fixed in each place of tracking area	Tags are small and lightweight; the battery life can last up to 5 years	Commercially available	The system cannot give absolute position measurements
WhereNet [54], [55]	Complex	Tags are small, lightweight and long battery life of up to 7 years	Commercially available	The accuracy of the system is not good enough
RADAR [57]	The system uses PC as APs, and does not address the issues with installation and maintenance	The system uses laptops as tracked targets, and does not consider the user preference	Not available	The system does not take advantages of the existing WLAN infrastructure in indoor environments
Ekahau [58]	The system reuses the WLAN infrastructures; the system needs several hours of site	Any WiFi device can be used as a tracked target; the tags are small, lightweight; the battery life is up to 5 years	Commercially available	The system needs site calibration time in the installation phase
COMPASS [61]	The system reuses the WLAN infrastructures	A device located at the end-user should contain a digital compass	Not Available	The system does not give real-time tracking services
Topaz [74]	There are many IR APs and servers need to be installed	The tracked tags need to be recharged every week	Commercially available	The delay of calculating the position of a tag is long (around 10 s - 30 s)
OPT [77]	Low	The tracked T-motes are small and lightweight, but its battery life is not long	Not available	The location measurement is not reliable
Ubisense [81]	Low, only sensors are used as infrastructures and four sensors can cover an area 400 m^2	The tracked tags are small and lightweight with battery life around 1 year	Commercially available	The UWB technology is new and the price of the system is high
MotionStar [83]	Small coverage area with 3 m in length; it is not scalable	The tracked sensors are connected via wire to RF transmitters; RF transmitters are heavy (about 1 kg) to wear; the battery life is around 1-2 hours	Commercially available	The system is designed for short range mobility tracking
Easy Living [87]	Low, for example, two stereo cameras can cover a a single room	The users do not need to carry any positioning device	Commercially available	The image processing is complex and needs substantial processing power
Beep [89], [90]	Not complex	The users can use their own devices such as PDA, mobile phone, etc., as positioning devices	Not available	The audible sound technology is influenced by sound noise in indoor environments

complexity, user preference, availability and limitations, have been proposed to evaluate and compare these IPSs from the view of users in PNs. Each IPS, which uses a certain type of technology or a combination of two or more technologies, has its design purpose, and works well under certain situations. It is desirable that the location estimation service can work for different indoor environments and provide scalable positioning services. Thus, in future research, a combination of different existing communications technologies and location information from different sources should be considered to increase the scalability and availability of location estimation services [97]. In the conclusion part, the current location sensing technology developing interests are described, and some on-going location system projects are introduced. We hope that researchers can use the information in this survey paper to propose more accurate and flexible positioning and position-based services for the users in the future PNs.

ACKNOWLEDGMENT

This work was partially funded by the EU IST MAGNET Beyond Project and the Dutch Freeband PNP2008 Project.

REFERENCES

[1] M. Vossiek, L. Wiebking, P. Gulden, J. Wiehardt, C. Hoffmann, and P. Heide, "Wireless Local Positioning", *IEEE Microwave Mag.*, vol. 4, Issue 4, December 2003, pp. 77-86.
[2] C. di Flora, M. Ficco, S. Russo, and V. Vecchio, "Indoor and outdoor location based services for portable wireless devices", *Proc. 25th IEEE International Conference on Distributed Computing Systems Workshops*, 2005.

[3] K. Muthukrishnan, M. E. Lijding, and P. J. M. Havinga, "Towards Smart Surroundings: Enabling Techniques and Technologies for Localization", *Proc. International Workshop on Location-and Context-Awareness*, Berlin, Germany, 2005.

[4] M. Dru and S. Saada, "Location-based mobile services: The essentials", *Alcatel Telecommunications Review*, 2001, pp. 71-76.

[5] S. Bush, "A Simple Metric for Ad Hoc Network Adaptation", *IEEE J. Select. Areas Commun.*, vol. 23, no. 12, December 2005, pp. 2272-2287.

[6] E. Yanmaz and O. K. Tonguz, "Location Dependent Dynamic Load balancing", *Proc. IEEE Global Telecommunications Conference*, 2005.

[7] I. M. Niemegeers and S. M. Heemstra de Groot, "Research issues in ad-hoc distributed personal networking", *Wireless Personal Commun.*, vol. 26, no. 2-3, August 2003, pp. 149-167.

[8] B. Hofmann, H. Wellinhof, and H. Lichtenegger, "GPS: Theory and Practice", Springer-Verlag, Vienna, 1997.

[9] J. A. M. Ladd, K. E. Bekris, A. P. Rudys, D. S. Wallach, and L. E. Kavraki, "On the Feasibility of Using Wireless Ethernet for Indoor Localization", *IEEE Trans. Wireless Communications*, vol. 5, no. 10, October 2006, pp. 555-559.

[10] J. Hightower and G. Borriello, "Location sensing techniques", Technical Report UW CSE 2001-07-30, Department of Computer Science and Engineering, University of Washington, 2001.

[11] J. Hightower and G. Borriello, "Location Systems for Ubiquitous Computing", *IEEE Computer Society Press*, vol. 34, no. 8, 2001, pp. 57-66.

[12] E. Kovacs, M. Bauer, U. Javaid, and D. E. Meddour, "Context-aware Personal Networks in Beyond 3G Systems", *Workshop on Capturing Context and Context Aware Systems and Platforms*, Myconos, Greece, 2006.

[13] M. Depsey, "Indoor Positioning Systems in Healthcare", *Radianse Inc., White Paper*, 2003, http://www.cimit.org/pubs/ips_in_healthcare.pdf.

[14] IST-027396 MAGNET/B/WP1/IR 1.4.1, "Draft User Functionalities and Interfaces of PN Services", August 2006.

[15] MAGNET Beyond, 2008, www.ist-magnet.org

[16] G. Myles, A. Friday, and N. Davies, "Preserving Privacy in Environments with Location-Based Applications", *IEEE Pervasive Computing*, 2003, pp. 56-64.

[17] J. Hightower, B. Brumitt, and G. Borriello, "The location Stack: Layered Model For Location in Ubiquitous Computing", *Proc. 4th IEEE Intl. Conference on Mobile Computing System and Applications*, 2002.

[18] C. Becker and F. Durr, "On location models for ubiquitous computing", *Personal and Ubiquitous Computing*, vol. 9, no. 1, 2005, pp. 20-31.

[19] JSR-179 (Java Specification Request), Java Location API for J2ME, 2008, http://jcp.org/en/jsr/detail?id=179

[20] T. Yu-Chee, W. Shih-Lin, L. Hwa, and C. Chih-Min, "Location Awareness in Ad Hoc Wireless Mobile Networks", *IEEE Computer*, vol. 34, no. 6, 2001, pp. 46-52.

[21] J. C. Chen, Y. C. Wang, C. S. Maa, and J. T. Chen, "Network-Side Mobile Position Location Using Factor Graphs", *IEEE Trans. Wireless Communications*, vol. 5, no. 10, October 2006, pp. 46-52.

[22] G. Nuno-Barrau and J. M. Paez-Borrallo, "A New Location Estimation System for Wireless Networks Based on Linear Discriminant Functions and Hidden Markov Models", *EURASIP J. Applied Signal Processing*, vol. 1, no. 1, 2006, pp. 1-17.

[23] M. Brunato and K. Csaba, "Transparent location fingerprinting for wireless services", *Proc. Med-Hoc-Net*, 2002.

[24] A. Smailagic and D. Kogan, "Location sensing and privacy in a context-aware computing environment," *IEEE Wireless Commun.*, vol. 9, no. 5, 2002, pp. 10-17.

[25] T. Mundt, "Two methods of authenticated positioning", *Proc. 2nd ACM International Workshop on QoS and Security for Wireless and Mobile Networks*, Malaga, Spain, October 2006.

[26] S. A. Zekavat, H. Tong, and J. Tan, "A Novel Wireless Local Positioning System for Airport (Indoor) Security", *Proc. SPIE*, 2004.

[27] B. Brandherm and T. Schwartz, "Geo Referenced Dynamic Bayesian Networks for User Positioning on Mobile Systems", *Proc. International Workshop on Location-and Context-Awareness*, Berlin, Germany, 2005.

[28] C. Delakouridis, L. Kazatzopoulos, G. P. Marias, and P. Georgiadis, "Share the Secret: Enabling Location Privacy in Ubiquitous Environments", *Proc. International Workshop on Location-and Context-Awareness*, Berlin, Germany, 2005.

[29] A. Beresford, and F. Stajano, "Location Privacy in Pervasive Computing", *IEEE Pervasive Computing*, vol. 2, no. 1, 2003, pp. 46-55.

[30] R. Casas, D. Cuartielles, A. Marco, H. J. Gracia, and J. L. Falc, "Hidden Issues in Deploying an Indoor Location System", *IEEE Pervasive Computing*, vol. 6, no. 2, 2007, pp. 62-69.

[31] X. Fernando, S. Krishnan, H. Sun, and K. Kazemi-Moud, "Adaptive denoising at Infrared wireless receivers", *Proc. SPIE*, 2003.

[32] R. Want, A. Hopper, V. Falcao, J. Gibbons, "The Active Badge Location System", *ACM Trans. Information Systems*, vol. 10, no. 1, January 1992, pp. 91-102.

[33] A. Harter and A. Hopper, "A distributed location system for the active office", *IEEE Network*, vol. 8, no.1, 1994, pp. 62-70.

[34] A. Harter, A. Hopper, P. Steggles, A. Ward and P. Webster, "The Anatomy of a Context-Aware Application," *Proc. 5th Ann. Intl Conf. Mobile Computing and Networking (Mobicom 99)*, New York, 1999, pp. 59-68.

[35] Active Badge System, Web Site, 2008, http://www.cl.cam.ac.uk/ research/dtg/attarchive/ab.html

[36] Cybernet Interactive, Firefly Motion Capture System, 2008, http://www.cybernet.com/interactive/firefly/index.html

[37] "Firefly Motion Tracking System User's guide", 1999, http://www.gesturecentral.com/firefly/FireflyUserGuide.pdf

[38] Northen Digital Inc. Website, Optotrak, 2008, http://www.ndigital.com/

[39] R. States and E. Pappas, "Precision and repeatability of the Optotrak 3020 motion measurement system", *J. Medical Engineering and Technology*, vol. 30, no. 1, 2006, pp. 1-16.

[40] E. Aitenbichler, M. Mhlhuser, "An IR Local Positioning System for Smart Items and Devices", *Proc. 23rd IEEE International Conference on Distributed Computing Systems Workshops (IWSAWC03)*, 2003.

[41] C. Lee, Y. Chang, G. Park, J. Ryu, S. Jeong, and S. Park, "Indoor Positioning System Based on Incident Angles of Infrared Emitters", *Industrial Electronics Society*, 2004.

[42] Active Bat website, 2008, http://www.cl.cam.ac.uk/research/dtg/attarchive/bat/

[43] A. Ward, A. Jones, and A. Hopper, "A New Location Technique for the Active Office", *IEEE Personal Communications*, vol. 4, no. 5, October 1997, pp. 42-47.

[44] N. Priyantha, A. Chakraborty, and H. Balakrishnan, "The cricket location- support system", *Proc. ACM Conference on Mobile Computing and Networking*, 2000.

[45] N. B. Priyantha, "The Cricket Indoor Location System", PhD thesis, MIT, 2005.

[46] Sonitor System Website, 2008, http://www.sonitor.com/

[47] Y. Fukuju, M. Minami, H. Morikawa, and T. Aoyama, "DOLPHIN: An Autonomous Indoor Positioning System in Ubiquitous Computing Environment", *Proc. IEEE Workshop on Software Technologies for Future Embedded Systems*, Hakodate, Japan, May 2003.

[48] H. Piontek, M. Seyffer, and J. Kaiser, "Improving the Accuracy of Ultrasound-Based Localisation Systems", *Proc. International Workshop on Location-and Context-Awareness*, Berlin, Germany, 2005.

[49] T. Lin and P. Lin, "Performance comparison of indoor positioning techniques based on location fingerprinting in wireless networks", *Proc. International Conference Wireless Network, Communications and Mobile Computing*, vol. 2, June, 2005, pp. 1569-1574.

[50] K. Kaemarungsi and P. Krishnamurthy, "Properties of indoor received signal strength for WLAN location fingerprinting", *Proc. 1st Annual International Conference on Mobile and Ubiquitous Systems: Networking and Services (MobiQuitous '04)*, Boston, Mass, USA, August 2004, pp. 14-23.

[51] L. M. Ni and Y. Liu, "LANDMARC: Indoor Location Sensing Using Active RFID", *Proc. IEEE International Conference on Pervasive Computing and Communications*, 2003, pp. 407-416.

[52] H. D. Chon, S. Jun, H. Jung, and S. W. An, "Using RFID for Accurate Positioning," *Proc. International Symposium on GNSS*, Sydney, Australia, December, 2004.

[53] K. Finkenzeller, "RFID-Handbuch", Hanser Fachbuch, 1999. Also available in English as RFID Handbook: Radio-Frequency Identification Fundamentals and Applications, John Wiley and Sons, 2000.

[54] Zebra Technology Company Web Site, 2008, http://www.wherenet.com/

[55] WhereNet Web Site , 2008, http://edu.symbol.com/docent authorware/WhereNet/intro/intro_1.asp

[56] Radianse Web Site, 2008, http://www.radianse.com/

[57] P. Bahl and V. Padmanabhan, "RADAR: An in-building RF based user location and tracking system", *Proc. IEEE INFOCOM*, vol. 2, March 2000, pp. 775-784.

[58] Ekahau, 2008, http://www.ekahau.com/

[59] Y. Wang, X. Jia, and H. K. Lee, "An Indoor wireless positioning system based on wireless local area network infrastructure", *Proc. 6th International Symposium on Satellite Navigation Technology Including Mobile Positioning and Location Services*, 2003.

[60] T. Kitasuka, K. Hisazumi, T. Nakanishi, and A. Fukuda, "WiPS: Location and Motion Sensing Technique of IEEE 802.11 Devices", *Proc. 3rd International Conference on Information Technology and Applications (ICITA'05)*, vol. 2, 2005, pp. 346-349.

[61] T. King, S. Kopf, T. Haenselmann, C. Lubberger and W. Effelsberg, "COMPASS: A Probabilistic Indoor Positioning System Based on 802.11 and Digital Compasses", *Proc. First ACM Intl Workshop on Wireless Network Testbeds, Experimental evaluation and CHaracterization (WiNTECH)*, Los Angeles, CA, USA, September, 2006.

[62] P. Prasithsangaree, P. Krishnamurthi, and P. K. Chrysanthis, "On indoor position location with wireless LANs", *Proc. 13th IEEE Intl Symposium on Personal, Indoor and Mobile Radio Communications*, September 2002.

[63] C. Gentile and L. Klein-Berndt, "Robust location using system dynamics and motion constraints", *IEEE International Conference on Communications (ICC)*, vol. 3, June 2004, pp. 1360 - 1364.

[64] M. Youssef, A. Agrawala, "Handling samples correlation in the Horus system", *Proc. IEEE INFOCOM*, vol. 2, 7-11 March 2004, pp. 1023 - 1031.

[65] Y. Chen, Q. Yang, J. Yin, and X. Chai, "Power-Efficient Access-Point Selection for Indoor Location Estimation", *IEEE Trans. Knowledge and Data Engineering*, vol. 18, no. 7, 2006, pp. 877-888.

[66] D. Madigan, E. Elnahrawy, R. P. Martin, W. Ju, P. Krishnan amd A. S. Krishnakuman, "Bayesian Indoor Positioning Systems", *Proc. IEEE INFOCOM*, vol. 2, 2005, pp. 1217-1227.

[67] H. Satoh, S. Ito, and N. Kawaguchi, "Position Estimation of Wireless Access Point Using Directional Antennas", *Proc. Intl Workshop on Location-and Context-Awareness*, Berlin, Germany, 2005.

[68] S. Thongthammacharl and H. Olesen, "Bluetooth Enables In-door Mobile Location Services," *Proc. Vehicular Technology Conference*, vol. 3, April 2003, pp. 2023-2027.

[69] R. Bruno and F. Delmastro, "Design and Analysis of a Bluetooth-Based Indoor Localization System", *Proc. Personal Wireless Communication (PWC 2003)*, Venezia, Italy, September 2003.

[70] M. Rodriguez, J. P. Pece, and C. J. Escudero, "In-building location using Bluetooth", *Proc. IWWAN*, 2005.

[71] J. Hallberg, M. Nilsson, and K. Synnes, "Positioning with Bluetooth", *Proc. 10th Intl Conference on Telecommunications*, 2003.

[72] A. Genco, "Three step bluetooth positioning", *Lecture Notes in Computer Science*, vol. 3479, 2005, pp. 52-62.

[73] S. Kawakubo, A. Chansavang, S. Tanaka, T. Iwasaki, K. Sasaki, T. Hirota, H. Hosaka, and H. Ando, "Wireless Network System for Indoor Human Positioning", *Proc. 1st Intl Symposium on Wireless Pervasive Computing*, 2006, pp. 1-6.

[74] Topaz, 2004, www.tadlys.com/pages/Product_content.asp?iGlobalId=2

[75] J. C. F. Michel, M. Christmann, M. Fiegert, P. Gulden, and M. Vossiek, "Multisensor Based Indoor Vehicle Localization System for Production and Logistic", *Proc. IEEE Intl Conference on Multisensor Fusion and Integration for Intelligent Systems, Heidelberg*, Germany, September 2006, pp. 553-558.

[76] D. Niculescu and R. University, "Positioning in Ad Hoc Sensor Networks", *IEEE Network Magazine*, vol. 18, no. 4, July/August 2004.

[77] X. An, R. Venkatesha Prasad, J. Wang, and I. G. M. Niemegeers, "OPT: Online Person Tracking System for Context-awareness in Wireless Personal Network", *Proc. Mobihoc*, 2006.

[78] Tmote Sky, 2008, www.moteiv.com

[79] S. J. Ingram, D. Harmer and M. Quinlan, "UltraWideBand Indoor Positioning Systems and their Use in Emergencies," *Proc. IEEE Conference on Position Location and Navigation Symposium*, April 2004, pp.706-715.

[80] Y. Zhang, W. Liu, Y. Fang, and D. Wu, "Secure localization and authentication in ultra-wideband sensor networks", *IEEE J. Select. Areas Commun.*, vol. 24, no. 4, 2006, pp. 829-835.

[81] Ubisense, 2008, http://www.ubisense.net

[82] F. Raab, E. B. Blood, T. O. Steiner, and H. R. Jones, "Magnetic Position and Orientation Tracking System", *IEEE Trans. Aerospace and Electronic Systems*, vol. AES-15, no. 5, September 1979, pp. 709-718.

[83] MotionStar Wireless Wbsite, 2007, http://www.ascension-tech.com/products/motionstarwireless.php

[84] J. Krumm, S. Harris, B. Meyers, B. Brumitt, M. Hale, and S. Shafer, "Multi-Camera Multi-Person Tracking for Easy Living", *Proc. 3rd IEEE Int'l Workshop Visual Surveillance*, IEEE Press, Piscataway, 2000.

[85] D. Focken and R. Stiefelhagen, "Towards vision-based 3-D people tracking in a smart room", *Proc. 4th IEEE Intl Conference on Multimodal Interfaces*, October 2002.

[86] V. Paelke and C. Reimann, "Vision-Based Interaction - A First Glance at Playing MR Games in the Real-World Around Us", *Proc. 3rd Intl Conference on Pervasive Computing (PERVASIVE 2005)*, 2005.

[87] B. Brumitt, B. Meyers, J. Krumm, A. Kern, and S. Shafer, "Easyliving: Technologies for intelligent environments", *Handheld and Ubiquitous Computing*, 2000.

[88] A. Madhavapeddy, D. Scott, and R. Sharp , "Context-Aware Computing with Sound," *Proc. 5th Intl Conference on Ubiquitous Computing*, October 2003.

[89] C. V. Lopes, A. Haghighat, A. Mandal, T. Givargis, and P. Baldi, "Localization of Off-the-Shelf Mobile Devices Using Audible Sound: Architectures, Protocols and Performance Assessment", *ACM SIGMOBILE Mobile Computing and Communication Review*, vol. 10, Issue 2, April 2006.

[90] A. Mandal, C. V. Lopes, T. Givargis, A. Haghighat, R. Jurdak, and P. Baldi, "Beep: 3D Indoor Positioning Using Audible Sound", *Proc. IEEE Consumer Communications and Networking Conference*, Las Vegas, January 2005.

[91] C. A. Patterson, R. R. Muntz, C. M. Pancake, "Challenges in Location-Aware Computing", *IEEE Pervasive Computing*, vol. 2, no. 2, 2003, pp. 80-89.

[92] C. Schmitt and O. Kaufmann, "Indoor Navigation with SVG", 2005, http://www.svgopen.org/2005/papers/IndoorNavigationWithSVG/index.html

[93] J. Petzold, A. Pietzowski, F. Bagci, W. Trumler, and T. Ungerer, "Prediction of Indoor Movements Using Bayesian Networks", *Proc. International Workshop on Location-and Context-Awareness*, Berlin, Germany, 2005.

[94] MERL website, 2008, http://www.merl.com

[95] CSIRO website, 2008, http://www.csiro.au/csiro/channel/_ca_dch2t.html

[96] AeroScout website, 2008, http://www.aeroscout.com/

[97] A. LaMarca, et al., "Place Lab: Device Positioning Using Radio Beacons in the Wild", in Proceeding of the *3rd Int. Pervasive Computing Conference*, vol. 3468, 2005, pp. 116-133.

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