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Indoor Localization Systems
– Tracking objects and personnel with sensors, wireless networks and RFID

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Abstract: Advances in ubiquitous mobile computing and rapid spread of information systems have fostered a growing interest in indoor location-aware or location-based technologies. In this paper we will introduce the primary technologies used in indoor localization systems by classifying them in three categories: Non-RF technologies, Active-RF technologies and Passive-RF technologies. Both commercialized products and research prototypes in all categories are involved in our discussion. The Passive-RF technologies are further divided into "Mobile tag" and "Mobile reader" systems. We expect such classification can cover most of the indoor localization systems. Features of these systems are briefly compared at the end of this paper.
Keywords: RTLS, Indoor localization, RFID

Introduction

An information system is always expected to provide answers to four types of questions: Who, What, When and Where. Information such as ID, time and incident descriptions can be useless if it is not associated with a physical location. With the growing requirements in mobility of the end devices, a Real-Time Locating System/Service (RTLS) has become an integrant part of many information systems. The most well known localization service is the Global Positioning System (GPS) using a network of 24 beacon satellites to cover the majority of the earth's surface. It is widely used to track and navigate only moving objects outdoors, because its accuracy cannot satisfy most indoor applications and the satellite signal itself is usually unreachable in indoor environment. Thus dedicated systems have to be used for on-site localization. Compared to outdoor applications, the indoor environment is more complex, irregular, unpredictable and inconsistent. Because of this it is very hard for a system to achieve satisfied performance in all the aspects including accuracy, range, power consumption, implementation, cost and maintenance. Most designs have to looking for balance between these parameters.

Many new technologies have emerged in the past decade to achieve accurate and reliable tracking of objects within buildings, the performance of indoor localization has improved significantly. Different systems have been designed for various applications. The application scale varies from tracking thousands of objects and personnel in industry and public applications to navigating a single vacuum cleaner in home automation system. The current research in indoor localization technology can be classified in three categories: Non-RF technology, Active-RF technology and Passive-RF technology. The Passive-RF technologies can be further divided into "Mobile tag" and "Mobile reader" systems. For the remaining of this paper we will introduce and discuss the primary technologies based on this classification.

Non-RF Technology

As most of the current indoor tracking systems today use radio frequency we link all other technologies together as non-RF technologies and discuss them here. Such technologies include inertial, video image processing, infrared (IR) and Ultrasound.

Inertial localization is the tracking approach with the simplest system architecture. As no network or even reference points are needed. The mobile objects operate a 'stand alone' system which uses self-contained sensors to measure its own movement, such as the variables of distance moved, orientation of movement, acceleration and velocity etc. Based on this sensing information the system is able to estimate the current position of the device relative to its starting point. If the starting point can be specified on a pre-learnt map the system will be able to generate the absolute location of the mobile object on it. An example of the inertial system can be found in Collin's work [1]. Such systems suffer poor localization accuracy especially in long term observations due to drift and error accumulation.

Video image processing is another technology with a relatively simple system architecture. Video systems usually do not require the mobile objects to carry any additional devices. Current technologies can determine numbers, human faces and even body motions from video clips [2]. Object or human localization can be done using such systems but line of sight requirement, large amount of computer processing and imperfect identification error rate prevent the technology from being adopted in commercial applications.

Infrared (IR) is one of the most common approaches in Non-RF system. In such system mobile objects are equipped with infrared emitters to transmit their ID information via modulated infrared light. Receivers are deployed in the environment to cover the area that the mobile objects can reach. When the infrared light is received by a particular receiver, the location of the mobile object can be determined within a predefined area around the receiver. The Active Badge developed by AT&T is one example application adopting this technology [3]. The disadvantages of infrared systems include requiring line-of-sight connection between emitter and receivers, short range signal transmission and low localization accuracy.
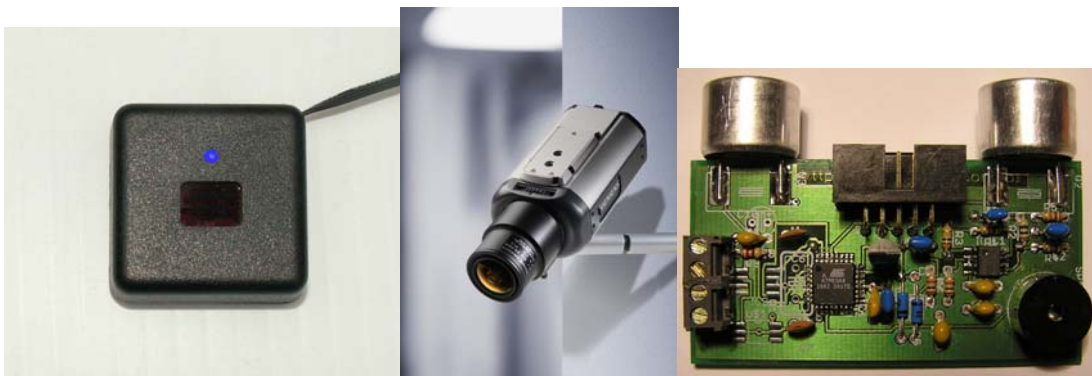

Figure 1: IR sensor (left), Video camera and ultrasound node

Ultrasound is the most popular technology used in Non-RF systems. Its main advantage is that it is able to provide very high localization accuracy. This is because the speed of ultrasound is relatively slow which consequently gives the system more time to perform range measurement calculations. The MIT Cricket system is a primary example of the use of ultrasound in indoor environment tracking with a granularity of a few feet [4]. But like the infrared systems, line-of-sight requirement between emitters and receivers is a disadvantage of ultrasound positioning. It also requires a complicated and costly system infrastructure.

Non-RF technologies all have unresolved weakness such as low localization accuracy, short operating range and the need for line of sight connection. Those problems have prevented the growing of Non-RF technologies and most of the interest nowadays has been turned towards RF-based technologies.

Active-RF Technology

Due to the unsolvable problems that the Non-RF technologies encountered described above, more and more indoor localization systems are using RF based technologies for range measurement. Radio frequency does not require strict line of sight path for transmission, this makes the site survey and system implementation much easier. In addition, some of the radio frequency based wireless data networks are already in use in many buildings; they can therefore be upgraded to support the localization applications with little or no hardware change.

Most of the research in RF based indoor localization use Active-RF systems. Much works have been done in system design, locating algorithm and implementation of such systems. But the basic approach of these systems are similar, this is to deploy base stations in the environment and to calculate location based on the base station signals received by the mobile nodes carrying on mobile objects. We note that for Active-RF systems there are three main features which identify each project: its range measurement approach, position estimation algorithm and network standard.

The first feature is the way range is measured between the mobile nodes and the base stations. The range measured by the mobile nodes can be absolute distance, relative distance, relative direction or even just RF connectivity. RF connectivity does not require any additional function in the data network hardware. Each mobile node will be considered to be "connected" to those base stations it can hear. The Angle of Arrive (AOA) technique can compute the relative direction of a signal source to a base station by using directional antennas. The Time of Arrival (TOA) and Time Difference of Arrival (TDOA) techniques calculate the absolute distances between mobile node and the base stations, simply by multiplying the speed of light with the RF travel time in the air. These techniques require very accurate device clock and network synchronization, as a small clock drift can lead to very large distance measurement error (about 30cm per ns drift). This increases the hardware cost of TOA and TDOA systems. Received Signal Strength (RSS) and Bit Error Rate (BER) are two parameters that are both proportional to

the distance. They can be used to describe the relative distances between mobile node and base stations. RSS and BER techniques do not have very strict requirement to hardware and can easily be supported by low level processors.

The second feature is the design of algorithms to estimate the mobile node location based on the distance, direction or connectivity of data gathered. If the AOA information of a mobile node is gathered from multiple base stations then its position can be calculated by the intersection point of the lines coming out of the base stations towards the mobile node's direction. For 2-D localization, a node's AOA data from 2 base stations can be enough to locate it. If we obtain just the connectivity information of a node to the base stations, we can use Centroid algorithm. It simply calculates the average position of all the base stations that the node can hear. When absolute distance or relative distance data is gathered, there are several algorithms we can choose from. Proximity algorithm locates the node within the RF range of the closest base station to it. The systems using Triangulation algorithm will draw circle around each base station based on the distance measurements from the node, each circle represents a possible area for the node position, and the intersection of all these circles is the node location. The problem of all the above algorithms is that they haven't considered the multipath affect in RF transmission. Radio waves can be reflected by walls, floors and obstacles before arriving at the receiver's antenna; even it can penetrate these objects it attenuates faster in them then in the air. This means the signals arrived at a receiver's antenna may not represent the relative distance or the source direction accurately. Actually, they are very unlikely to be correct in indoor environment. It is normal that a base station in the next room receives higher signal strength than the base station in the same room with the mobile node. The best approach to deal with multipath affect is the RF Fingerprinting algorithm. It is an algorithm widely used in current commercial indoor RTLS systems. This algorithm requires the system to be trained before normal operation. Samplings of the RSS, TOA or BER data from all the base stations are performed at each point within the environment. The list of sampling results from all base stations at a same position is considered to be the fingerprint of this particular position. During normal operation the fingerprint information of a mobile node is sampled regularly and is compared to the fingerprints database the system has previously learnt to determine the node's current location. This algorithm significantly improved the indoor localization accuracy of Active RF systems.

The last feature is standard RF network in which the sensors and localization algorithms are implemented. The choice depends on cost, accuracy, range, data transmission capacity and existing network infrastructures on site etc. Options include Wi-Fi, Bluetooth, Active RFID, Ultra wideband (UWB), Wireless Sensor Network (WSN). The advantage of Wi-Fi is that such network infrastructure exists in many buildings, and localization technology can usually be adopted without any hardware modification. Most of the Wi-Fi localization systems are using TOA [5] or RSSI [6] measurements and Fingerprinting algorithm with an accuracy of 2 to 5 metres depending on site survey. Bluetooth Systems usually use RSS or BER and Triangulation with an accuracy of around 10 metres. SpotON [7] and LANDMARC [8] are two main indoor localization systems using active RFID technology. Both systems use active tags as mobile nodes and estimate the target node position by analyze the inter-tag RSS information. These systems

are still in prototype development and their actual accuracies are hard to compare. UWB has recently become a new means of indoor localization. It uses TDOA and Triangulation for position estimation. UWB base stations can send very short beacon pulse which can overcome the multipath problem that is a problem for the other RF technologies. Thus it can achieve an accuracy of 15cm for indoor environment [9]. MERIT [10] is a primary localization system using WSN. The researchers use RSS between nodes and base stations and estimate the node position at room level using the Proximity algorithm. They put RF reflectors beside the base stations to ensure the base station within the same room with the mobile node will receive the best RSS. In their experiments a 98.9% accuracy was achieved.
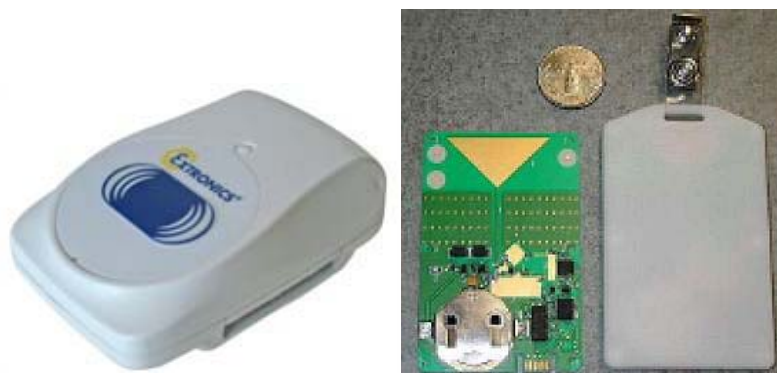

Figure 2: A Wi-Fi RTLS tag (left) and a UWB tag (right)

Wi-Fi localization may be the most popular technology used in current commercialized indoor localization systems, not only because it is a mature technology providing acceptable accuracy and hardware cost for most applications, but also because the 802.11 standard used by Wi-Fi is dominating most of the in building wireless local area data network solutions. This means the customers may not need to purchase a whole set of localization system infrastructure if it is already in their buildings. Despite of the large market share of Wi-Fi localization, WSN and UWB based systems still have great potential in taking its place. WSN system features even lower hardware and maintenance cost than Wi-Fi. Much work has been done in adopting WSNs in building security and fire safety applications; this is likely to happen in the near future and will make WSN a competitive technology for indoor localization. UWB has been proved to be the most accurate RF indoor localization technology as it does not have the multipath problem that the other RF systems encounter. The barrier for adopting UWB in commercialized systems is the cost, lack of standard and national RF regulations. Because UWB may act as noise in other RF systems working in licensed RF bands, it is still forbidden in some countries. Efforts are being made in both the business and academics research communities to overcome these problems and if successful, it is likely that UWB will replace Wi-Fi in applications in which the accurate location of objects is of primary importance irrespective of system costs.

Passive-RF System

Active-RF systems have complicated system infrastructures and relatively high cost in hardware and maintenance. They are usually adopted in large scale applications such as the tracking of patients inside a hospital [11] or tracking vehicles and machines within industrial plants and warehouses [12]. For some smaller applications like home automation or assisting the visually impaired, Passive-RF systems which have much simpler designs and implementation are preferable.

In Passive-RF systems either the node attached to the target object or the reference nodes implemented in the environment are simple passive circuits which do not need access to mains power or battery. These passive nodes act as attached reference points and do not work until an assorted reading device is present nearby. Passive Radio Frequency Identification is the most commonly used technology for Passive-RF systems. The passive tags, or backscatters, are first designed to replace the barcode used for object identification. With no power resource and RF transmitter, they use inductive/propagation coupling to connect with the tag reader's antenna. This means that the passive tags just simply reflect back the signal emitted by the reader. These passive tags are simpler, cheaper and have a read range from 0.1cm to 10m depends on frequency band used.

The Mobile Tags

For some applications, the accuracy of tracking is only required at room level or building sector level. For such applications, RFID readers can be installed at the access points of each room or between different sectors of the building. Objects or persons to be tracked are equipped with passive RFID tags. By monitoring the information presented by the tag at each access point it has responded to, the system is able to determine its location within a specific room or a building sector. Such systems are easy to implement and maintain, but suffer a lack of real-time access to the objects position. Many people think RFID can provide real-time location information of the tags, but actually all it can provide is the location of a tag when it last passed a reader device [13]. Thus the object locations in the systems using access points are not based on instant tag query, but on presumptions made from the limited log of readings.

If an application requires more accuracy or if instant access to the tracking nodes is preferred, dense reader deployment will be necessary in order to make sure tagged objects are always within the range of at least one reader antenna. "Smart Shelf" is an example of dense reader deployment designed for a supermarket environment [14]. Reader antennas are mounted on each layer in every shelf to give full radio coverage to all the goods on display. Such system can provide real-time location of all the merchandise at item level by request of both staff and customers. After integrating the smart shelf with the store inventory management systems, it can also alert store personnel to refill particular merchandise or retrieve the out of date goods by continuously monitoring the number of them on the shelf and their product information. Leading

Supermarkets in the world such as Wal-mart, Tesco and Metro are all testing the smart shelf technology and are expecting a massive implementation of it in the near future.

Figure 3: Smart Shelves for books (left) and pharmaceuticals (right)

When passive RFID technology was first introduced, the standard infrastructure of its design was to have the reader devices mounted at fixed positions, and the tags attached to the mobile targets. Reader devices were designed to provide the upper layer server with the tags' information each time they presented themselves within the range of its antenna. The "access point" and the "smart shelf" applications are based on this infrastructure which can be described as the "Mobile tag" infrastructure. Although in the "smart shelf" system instant query to each item is possible, it is based on the fact that the position of the tracked objects (merchandise displayed on shelf) are relatively fixed and only within a particular sector of the building – the shelf. This has actually limited the ability of RFID to undertake real-time localization tasks. In specific applications when objects are mobile and need to be tracked in real-time, an even denser deployment of passive RFID readers is unavoidable to ensure the coverage of every minute area inside a building. In most cases the cost of the passive RFID readers makes such dense deployment impractical. On the other hand, passive RFID tags are originally proposed to be attached to massive moving objects, so they are designed to have very low cost which makes it feasible for large scale deployment with acceptable costs. This leads to another infrastructure for passive RFID localization technology, the "Mobile reader" infrastructure. In such systems passive RFID reader device are attached to the target objects, while a large number of passive tags are deployed in the environment to act as location marks. The location of an object is calculated based on the tags detected at any instant by the reader located on the object.

The "Mobile Readers"

One type of the "Mobile reader" systems being studied is the *passive RFID-assisted localization*. These systems focus on using passive RFID technology to calibrate their current localization approaches, which means the localization and navigation tasks are not solely based on passive RFID but use a combination of two or more different technologies. Tsukiyama has deployed passive RFID tags on the wall inside a building. A robot equipped with a reader device can use the tags as landmarks to help guide itself from one point to another using ultrasonic rangefinders [15]. Kulyukin et al. attached passive RFID tags to various objects and made a robot guide for the visually impaired

inside a building. This robot uses laser sensors [16] or ultrasonic sensors [17] to guide the robot and uses the RFID tags as landmarks. In [18], Miller et al. developed a system for first responders' localization using inertial sensors and the dead reckoning approach. Based on the system they studied, they proposed an option to implement passive RFID tags on the wall and floor inside buildings to assist the DR system and improve its performance. The researchers declared that they achieved enhanced accuracy of their inertial tracking systems by adding the assistance of passive RFID tags. Yang et al. [19] used a similar dead reckoning method calibrated by passive RFID tag array on the ground to locate and guide a robot in an indoor environment. They proposed a hexagon tag array and analyzed the uncertainty of the calibrating system. These RFID-assisted localization systems combine different technologies to perform tracking. Passive RFID technology is usually used only for calibration purpose, thus the accuracy of the systems vary and mainly depend on the main approaches they use.

Figure 4: Passive RFID tags deployed under carpet (left), Vorwerk's smart vacuum cleaner with built-in RFID reader (right)

The other type of "Mobile reader" systems is the *passive RFID-based localization*. For those systems the localization is completely based on a passive RFID system. Hahnel et al. [20] built a mobile robot localization system by deploying passive RFID tags on the wall inside an office building, and equipped tracked personnel with a two-antenna RFID reader. They studied the RFID reader antennas and established a sensor measurement likelihood model which describes the likelihood of detecting an RFID tag given its location relative to one of the antennas. With the antenna sensor model, a human motion model and a previous learnt site map, Monte Carlo localization was applied to estimate the movement of persons in the environment. The experimental results have shown a localization error of 2 to 3 metres after the system has been initialized and became stable. The system was further improved by Schneegans et al. in [21] using a RFID snapshot method. In this method they treat the list of detected tags along with the number of detections over a short measurement cycle as a feature vector, which they called a "snapshot", of each particular position in the environment. The system first needs to learn the snapshots at known positions in a training phase. Snapshots gathered by the reader during normal localization operations will be compared to the snapshots table established in training to estimate the movement of tracked robot or personnel. Such an idea is quite similar to the RF fingerprinting approach using by Wi-Fi indoor tracking systems introduced earlier in this paper. In their experiments after comparing their method with Hahnel's system, the researchers demonstrated their system providing similar accuracy, but with less computation overheads and faster converging outputs. The most systematic

research of the moving-reader systems is found in Bohn's works [22][23][24]. He proposed a Super-distributed RFID Tag Infrastructure in which he investigated all aspects of the system from tag distribution patterns to the design of dedicated middleware. Passive RFID tags are no longer deployed randomly in the environment, but in predefined grids under the floor. Bohn proved that by regulating the tag distribution patterns the tracking algorithm can be simplified and the localization error can become predictable and controllable. A further research in such RFID grids has been done by Koch et al. [25] by evaluating various passive RFID technologies. Willis et al. [26] tried to add more environment information in the tags in the grid besides their ID and coordinates. The information written in each tag depends on its location, for example, tags in a traffic pattern leading to a door may contain door location, type of handle and opening directions. They argued that using the information in the tags the mobile node can perform stand-alone self-localization, making the system more flexible while protecting the user privacy. All of the above systems calculate current target position based on the data from a reader indicating which tags are currently presenting within the reader antennas at the moment. Localization algorithms are simply the calculation of the geometric centre of the tags detected. A commercialized prototype of the super-distributed RFID infrastructure called "Smart Floor" [27] has been developed by German carpet and vacuum cleaner company Vorwerk, guiding their robot vacuum cleaners to perform cleaning work or transporting goods and persons (Figure 4). Recently Gueaieb and Miah [28] proposed an approach to estimate the angle between the mobile target orientation and the direction of a particular tag relative to it. Their mobile target is equipped with a passive reader with one transmitting antenna in the middle and two receiving antenna at both sides, the reader is designed to be capable of computing the phase information of the signals received. When the reader reads a particular tag the signal reflected back from the tag is received by both receiving antennas, by comparing the phase difference of the two receiving signals the relative direction of the tag can be estimated. Although the researchers in this project are using this technique for navigation of the mobile target, it has the potential to enable target self localization by estimating the relative direction of multiple tags using an approach similar to the AOA algorithm used in the active RF systems.

The idea of the "Mobile reader" infrastructure is mainly studied and applied in robot and vehicle localization and navigation. This is because the current passive RFID reader devices are relatively large in size; they also have relatively high power consumption and need to be supported by large capacity battery which makes further contribution to the size and weight of the final packaging; the last and the most important fact is that the passive RFID reader have quite restrict requirement in antenna and tag orientation while performing reading operations, it is easier to fix the antenna position and orientation on a robot than on a personnel whose pose and motion are much more complicated and unpredictable. But we have seen efforts in ongoing research works trying to solve such problem. With the advance in hardware design we can expect the RFID reader devices to become smaller and more power efficient in the next few years. It is likely that in the near future, the devices will become so small that solutions such as putting reader and antennas under the shoes will become possible.

The Passive-RF systems introduced in this section, especially the passive RFID-based systems, have relatively simple system infrastructure and are easy to implement. In "Mobile tag" systems the mobile nodes attached to tracked objects are low cost passive tags which are currently the only acceptable option for applications requiring one time disposable use of the nodes, such as shelf monitoring in supermarket and post tracking. Even for the general localization applications the "Mobile reader" systems are competitive. The reference nodes deployed over the environment are simple, cheap passive tags which do not need mains power or battery to be driven; this makes the cost of the systems lower and their maintenance easier than the Active-RF systems. The simple hardware design of these tags also means they are robust and are able to last for a long term in the environment which drives the system maintenance cost even lower. In addition, the mobile nodes use stand alone onboard self localization algorithm without any communication to a network or a server, cutting down the need for additional hardware and protecting end users' privacy. The whole system can also be considered to be turned off when no nodes is to be tracked, because if there's no mobile node/reader device in operation then there's no active device within the system. Those features of "mobile reader" Passive-RF systems make them preferable for some specific small scale applications with very limited number of mobile nodes to be tracked and discontinuous tracking operation. Examples of such applications include home service robots, such as a robot vacuum cleaner, and auto-assistant for the visually impaired. In these scenarios the tracked personnel or machines are limited in number and only need to be guided occasionally or during a specific period of the day. The adoption of Active-RF systems in these cases will be inefficient, costly and the user will need to keep a system/network infrastructure working all the day. Last but not least, passive tags have stronger resistance to tough environmental conditions and can be expected to provide assistant information to the first responders' applications during emergency incidences. A brief comparison of the main indoor tracking systems on market is shown in table 1.

	Infrared	Ultrasound	Wi-Fi	UWB	Mobile reader
Frequency Band	About 10^{14}Hz	> 20KHz	2.4GHz, 802.11a 5GHz	3.1-10.6 GHz	125KHz, 13.56 MHz, 868MHz, 2.4GHz
Range	Room	Room	< 100m	< 50m	0.1m-10m
Accuracy	0.3 m	0.1 m	2-5 m	0.15 m	0.2 m
Hardware Cost	Low	Medium	Medium	High	Medium
Beacon Always ON	Yes	Yes	Yes	Yes	No
Line of Sight	Yes	Yes	No	No	No
Power consumption	Low	Low	High	Low	High
Emit Orientation	No	Yes	No	No	Yes

Table 1. Comparison of main indoor tracking systems in the market

Conclusion

In this paper we introduced the primary technologies used in indoor localization systems. Both commercialized products and research prototypes are discussed. The technologies are classified in three categories: Non-RF technologies, Active-RF technologies and Passive-RF technologies. The Passive-RF technologies are further divided into "Mobile tag" and "Mobile reader" systems. Features of these systems were also compared. The trend of the proportion of RF-based indoor localization technology is still upwards. It is hard to compare the various RF-based systems which all have their own advantages and are suitable for specific applications. Although Wi-Fi localization systems are currently the most widely implemented indoor tracking systems, the "Mobile reader" Passive-RF technologies and UWB in Active-RF technologies have the potential to achieve solutions with better performance and will attract more interests in both enterprise and academics in the near future.

Reference

[1]. Collin, J. et al., *Indoor positioning system using accelerometry and high accuracy heading sensors. In Proceedings of GPS2003,* pp. 1164–1170, Portland, 2003

[2]. Cai, Q. et al., *Tracking Human Motion in an Indoor Environment*, *Proceedings of Second International Conference of Image Processing,* pp. 215-218, Washington, D.C., Oct. 1995

[3]. Want, R. et al., *The Active Badge Location System, ACM Transactions on Information Systems*, Vol. 40, No. 1, pp. 91-102, January 1992

[4]. Priyantha, N.B. et al., *The Cricket location-support system, Proceedings of the 6th annual international conference on Mobile computing and networking*, pp. 32-43, Boston, August 2000

[5]. Ciurana, M. et al., *Indoor tracking in WLAN location with TOA measurements, Proceedings of ACM Mobiwac 06*, pp. 121-125, Greece, 2006

[6]. Bahl, P. and Padmanabhan, V., *RADAR: An In-Building RF-based User Location and Tracking System. Proceedings of IEEE INFOCOM*, pp. 775-784, Tel-Aviv, Israel, March 2000

[7]. Hightower, J. et al., *SpotON: An indoor 3D location sensing technology based on RF signal strength. Technical report UW CSE 00-02-02*, University of Washington, Department of Computer Science and Engineering, Seattle, WA, February 2000

[8]. Lionel M. N. et al., *Landmarc: Indoor location sensing using active RFID. Proceedings of IEEE International Conference in Pervasive Computing and Communications 2003*, pp. 701-710, Dallas, March 2003

[9]. Ubisense UWB, http://www.ubisense.net/index.php?load=content&page_id=14

[10]. Lee, Y.W. et al., *MERIT: Mesh of RF sensors for indoor tracking, Proceedings of the Third Annual IEEE Communications Society Conference on Sensor, Mesh, and Ad Hoc Communications and Networks*, pp. 545–554, Reston, USA, Sept. 2006

[11]. Burnell, J., Hospital *Using RTLS to Monitor Patients' Conditions, RFID Update*, http://www.rfidupdate.com/articles/index.php?id=1309, (accessed 10/10/08)

[12]. Ibach, P.K. et al., *WLAN-based Asset Tracking for Warehouse Management, proceedings of IADIS International Conference e-Commerce*, Porto, Portugal, 2005

[13]. Ferguson, R.B., *Berkeley's Mesh Network: Dust in the RFID Wind*, http://www.eweek.com/article2/0,1895,2051310,00.asp, [04/11/06], (accessed on 07/12/06)

[14]. Healthcare-Packaging, RFID *smart shelves and cabinets*, http://www.healthcare-packaging.com/archives/2007/03/rfid_smart_shelves_and_cabinet.php, (accessed 14/10/08)

[15]. Tsukiyama, T., *World map based on RFID tags for indoor mobile robots, Proceedings of the SPIE, Vol. 6006*, pp. 412, Boston, USA, 2005

[16]. Kulyukin, V. et al., *RoboCart: Toward Robot-Assisted Navigation of Grocery Stores by the Visually Impaired. In Proc. of the 2005 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2005),* pp. 2845-2850, Edmonton, Alberta, Canada, 2005

[17]. Kulyukin, V. et al., *RFID in Robot-Assisted Indoor Navigation for the Visually Impaired. In Proc. of the 2004 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2004)*, pp. 1979-1984, Sendai, Japan, 2004

[18]. Miller, L.E. et al., *RFID-assisted indoor localization and communication for first responders. In Proc. of the Int. Symposium on Advanced Radio Technologies*, pp. 83-91, Boulder, USA, 2006

[19]. Yang, G. et al., *A RFID Landmark Navigation Auxiliary System, World Automation Congress (WAC),* Budapest, Hungary, July 2006

[20]. Hahnel, D. et al., *Mapping and localization with RFID technology, Proceedings of IEEE International Conference on Robotics and Automation, ICRA '04.,* pp. 1015-1020, Freiburg, Germany, 2004

[21]. Schneegans, S. et al., *Using RFID snapshots for mobile robot self-localization, Proceedings of the 3rd European Conference on Mobile*, pp. 241-246, Freiburg, Germany, Sept. 2007

[22]. Bohn, J. and Mattern, F., *Super-distributed RFID tag infrastructures, Proceedings of the 2nd European symposium on ambient intelligence*, pp. 1–12, Berlin Heidelberg, 2004

[23]. Bohn, J., *Prototypical implementation of location-aware services based on super-distributed RFID tags, Proceedings of the 19th international conference on architecture of computing systems*, pp. 69–83, Frankfurt, 2006

[24]. Bohn, J., *Prototypical Implementation of Location-Aware Services based on a Middleware Architecture for Super-Distributed RFID Tag Infrastructures. Personal and Ubiquitous Computing Journal*, Vol. 12, No. 2, pp. 155-166, ISSN 1617-4909, 2008

[25]. Koch, J. et al., *Indoor Localisation of Humans, Objects, and mobile Robots with RFID Infrastructure, Proceedings of Seventh International Conference on Hybrid Intelligent Systems*, pp. 271-276, Washington D.C., USA, 2007

[26]. Willis, S. and Helal, S., *RFID Information Grid for Blind Navigation and Wayfinding, Proceedings of the 2005 Ninth IEEE International Symposium on Wearable Computers (ISWC'05)*, pp. 34-37, Osaka, Japan, Oct. 2005

[27]. Vorwerk & Co. Teppichwerke GmbH & Co. KG, *Vorwerk is presenting the first carpet containing integrated RFID technology. Press release*, Hamlin, Germany, 2005

[28]. Gueaieb, W. and Miah, M.S., *Experiments on a novel modular cost effective RFID-based mobile robot navigation system, Proceedings of the IEEE International Conference on Systems, Man, and Cybernetics*, pp. 1658-1663, Montreal, Canada, Oct. 2007