Indoor Positioning: A Review of Indoor Ultrasonic Positioning systems

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Abstract— **In order to provide location information for indoor applications and context-aware computing, a lot of research is being done since last decade for development of real-time Indoor location system. In this paper, we have investigated indoor location concepts and have focused two major technologies used in many indoor location systems i.e. RF and ultrasonic. An overview of various RF systems that use different RF properties for location estimation has been given. Ultrasonic systems have been reviewed in detail as they provide low cost fine grained location systems. A few well known ultrasonic location systems have been investigated with a comparison of the system based on performance, accuracy and limitations.**

Keywords-Indoor location system; Radio Frequency; Ultrasonic; Time of Arrival; Lateration

I. INTRODUCTION

Research and development of real-time location systems started decades before, targeting military and civilian needs for navigation and target tracking, resulting in development of the high tech Global Positioning System (GPS). GPS architecture [1] has space and ground segments controlled by US Department of Defense and user segment i.e. GPS receiver that provides services to the user or system. A constellation of 24 satellites orbit the earth and provide coverage across the globe. Trilateration is used for location estimation and true location is estimated with help of four satellites in line-of-sight. Applications of GPS have extended diversely in missile guidance, vehicle and person tracking, clock synchronization in cellular systems, geographic information system, surveying, mapping etc. Unfortunately, drastic attenuation of GPS signals indoors and lack of line of sight limits its availability for indoor use. Therefore, research for the development of real-time indoor location systems (ILS) has been on the rise since last decade. ILS's find a large number of applications indoors including navigation assistance for robotics and disabled individuals having difficulties in way finding, tourist guidance in Museums and airports, context aware intelligent services for personal networks, locating patients and medical personals in hospitals. Location information is also required in the modern wireless sensor network based remote health monitoring systems.

In this article, we have given an overview of ILS's, discussed various techniques employed in implementation of ILS's in general and have discussed RF and US ILS's. A review of literature [2], [3], [4], shows various technology options for the design of an ILS which may be ultrasonic(US), infrared (IR), radio-frequency (RF) based systems which may be radio-frequency identification (RFID), received signal strength (RSS) of RF signals, Bluetooth, wireless local area network (WLAN), ultra-wideband (UWB), camera based vision analysis etc. We have explained US technology and its use in location estimation and discussed certain ultrasonic systems in detail, characterized them based on technology, cost and accuracy.

II. AN OVERVIEW OF INDOOR LOCATION SYSTEMS

In practice, there are many diverse applications of ILSs and each application has its own requirements and there is no lone positioning system which suits all kinds of applications, requirements and physical environments. Hightower and Borriello have proposed a taxonomy [5], which provides useful to guide application developers. A location system is classified based on certain parameters such as system scalability, cost, coverage area, capacity, accuracy, and precision.

In general, the architecture of positioning systems based on equipment can be classifies as Infrastructure and Mobile Devices. Infrastructure is the main components in the system offering support to location estimation. e.g. GPS, satellites. In ILSs, these are sometimes called base station, beacons, transmitters etc. The mobile devices are receivers connected to the user whose location is to be calculated. e.g. GPS receiver, a listener or a receiver or a mobile device.

A location system has three phases in deriving location information as shown in **Figure 1** i.e. physical quantity that is to be measured, measurement method and finally the extraction of useful location information based on the measurements. Sensing devices make use of any of signals like US, RF, IR or Vision to measure physical quantity for location. These signals travel between transmitters and receivers and also carry co-ordinate information of reference nodes. Than various methods are applied to calculate the physical quantity like measuring time of arrival (TOA), time different of arrival (TDOA), angle of arrival (AOA), received signal strength (RSS) etc. With the raw information of a physical quantity measured, various techniques and algorithms are used which transform raw data into usable position information. Techniques have been classified as triangulation/trilateration, Scene Analysis, Proximity [6] and fingerprinting [7]. Position estimated by algorithms may be relative or absolute and it varies from system to system like GPS estimates absolute positioning for every located device.

However, translation [5] between relative and absolute position estimates can be performed.

Most of the developed systems fall in the category of US and RF based location systems. Every system has different performance and accuracy and has certain advantages and limitations. In this article, we have focused US systems, however, a brief description of RF systems is given in the next section. US based ILS's are termed as fine-grained systems having centimetre level location accuracy. Also cost of US ILS is low compared with other systems, therefore, we have discussed in details US ILS.

Indoor location information can be used to build tools for navigating in unfamiliar buildings, including guiding a traveller to gates in an airport, helping users navigate (underground) train stations, helping visitors in a museum, directing visitors in an office building.

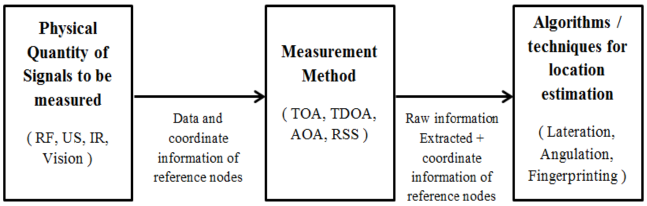

Figure 1: Phases of Location estimation

III. RF BASED ILS:-

RF systems estimate user location by measuring different properties of RF signals. Therefore, RF systems can be subdivided into various systems which make use of different RF properties namely RSSI, RFID, UWB, RADAR etc. to provide location estimation.

RF Received Signal Strength Information (RSSI) has been employed for many different location estimation systems[8], [9]. Performance of RSSI based location systems is highly effected by errors in signal strength resulted from multipath fading, reflection, shadowing, diffraction etc. most of RSSI based systems have been developed using existing infrastructure of WLAN, resulting in very low cost system. These systems use trilateration/triangulation or fingerprinting techniques for estimation. Reference [9] Present implementation of a low cost RSSI-based indoor location system, providing 3D location along-with real-time orientation information using magnetic compass. Position is estimated using trilateration. Low complexity and flexible accuracy refinement algorithm was proposed to obtain high precision indoor location. User indoor position is updated synchronously in virtual reality to real physical world. However, location update time is 3 seconds which is large, also large memory is required to store the location information in virtual reality with respect to actual physical environment. Experiments are performed in controlled environment and on small scale and validity of the system have to be tested in large scale and complex environments.

A prototype of an RSSI based tracking system has been presented [8] aiming to track a user position both in indoor and outdoor environments. A smoothing algorithm with low complexity is proposed to filter out erroneous RSSI values caused by dynamic fluctuation of radio signal. However performance of system was tested in minimal interference environment and with all reference nodes and mobile node were in LOS which may not be the case in real-time scenarios. The system estimates location with accuracy of 1.7m.

Another RSSI based location system presented in [10] uses fingerprinting to calculate location of a user. A database is created which calculates spatiotemporal RSS values in a specific environment to constitute a fingerprint of various points.

RFID systems provide low cost location systems having advantages in non-line-of sight environments and consist of RFID readers and tags. RFID readers transmits RF signal and in response tags reflect the signal after adding information by modulation. Tags can be active [11] or passive [12] or may use both active and passive tags [13] to support indoor location estimation of mobile devices. Passive tags do not have battery, providing unlimited lifetime. These are very cheap but operate only at a limited range. However, active tags are battery powered, offering much higher range.

UWB location systems [14], [15], are low cost systems, benefitting from the better power efficiency, higher temporal resolution and robustness to multipath fading of UWB signals [16]. An UWB location system consists of reference nodes with known location and active tags whose location is to be estimated. Four reference nodes are needed to accurately estimate location of tag, whereas more reference nodes increase the accuracy. However, there are certain coexistence constraints for UWB and other co-located radios.

An in-building RADAR, an RF based indoor locating system, has been presented in [17] developed by Microsoft Research for locating users. This location information is useful for enabling the use of location aware services and applications inside office. A user location is estimated by first estimating distance using RSS from three base-station nodes which is used to locate user position using triangulation. Accuracy of location estimated is 2 – 3 meters i.e. almost a typical office room level estimate.

IV. ULTRASONIC

US location systems offer a number of advantages over the other ILSs in terms of low system cost, reliability, scalability, high energy efficiency and most importantly zero leakage between rooms. US ILS's provide fine-grained location with centimetre level accuracy. US systems can also track multiple mobile nodes at one time i.e. higher capacity of location system to serve many users simultaneously

US locations systems rely on TOF measurement of US signal, calculated using velocity of sound. But unlike RF signals, velocity of sound in air does not remain constant and varies largely with environmental condition especially humidity and temperature [18] High humidity causes US signal to fade away quickly and travel short distance. The most pronounced effect of speed of sound is due to temperature which has direct effect on it. Speed of sound is:

$$v_{us} = 20.05\sqrt{T}$$

Where T is in kelvin. And speed of sound varies by approx. 0.18% for every 0C. Therefore, temperature effect cannot be tolerated and every US location system employs temperature sensor in order to avoid incorrect location estimates. Another challenge to US systems is offered by high levels of environmental US noise. If noise is non-persistent, erroneous location estimates are filtered by use of suitable algorithms but persistent noise sources degrade system performance.

US systems that have been developed use either narrowband or wideband. Each system has associated advantages and limitations. Narrowband waves travel longer distances, need less emitter power and hardware complexity. Limitations occur in multiple accesses for different emitters due to lack of signal identification and receiver is unable to distinguish between signals from different emitters. On the other hand, wideband systems overcome certain limitations of narrowband systems and offer multiple access by use of spread spectrum signaling techniques. Wideband systems also provide robustness to overcome interference. Certain limitations associated are the rapid attenuation of wideband signals, resulting in use of more power emitters and also use of complex hardware. Accuracy & precision of an US system depends on latency and update rate. Measure of system expected error in terms of physical distance gives accuracy and expectancy of how often a user location estimates within the stated accuracy is precision. The frequency of producing location estimates is the system's update rate, higher update rate results in higher precision and accuracy. System's performance also depends on how long it takes to produce an estimate for a single location.

In next section, we will discuss some well-known US systems that have been implemented by various labs and research groups.

A. Cricket

Cricket indoor location system [19] based on TDOA of Ultrasonic and RF signals has been developed by MIT laboratories, that provides space, position and orientation information. It involves design and implementation of beacon and listener nodes with active beacon-passive listener architecture. Beacons are fixed reference nodes attached to ceiling while listener is a mobile node attached to a device whose location is to be known. Coordinate assignment of beacons is auto and performed through MAT (mobile assisted topology generation) and AFL (anchor free localization) eliminating the need for manual coordinate assignment. RF signals provide a reference time to calculate speed of ultrasonic signals to calculate time of flight in a simple way. RF message is transmitted by beacons periodically that contain a unique beacon identifier, coordinate information, and temperature information. At the start of RF message, beacon transmits a 40 KHz US pulse of 150 µs.

Cricket uses a distributed architecture which puts certain constraints on the system like beacons scheduling, detection of US signals from a specific beacon and interference of ultrasonic signals that may result in large errors in location estimation. In order to coup up with these constraints, a number of algorithms have been developed and implemented in Cricket that include beacon scheduling, interaction detection, outlier rejections. Interference avoidance and detection at beacons and listeners and algorithm for filtering incorrect sample by history based filtering are employed in Cricket. Each node has temperature sensor in order to minimize estimation error that may be caused due to varying speed of sound at different temperatures. Beacon transmits this temperature information to listener in the RF message and an average of beacon and listener temperature is used. All location estimation calculation are done at listener and passive listener adds to the effectiveness of system as it can address to location need of a large number of listener nodes simultaneously. Also privacy is maintained as a listener does not send any information. This feature can be god for certain applications but on the other hand, it also limits the use as with a user's location information, many other needs can be addressed. Orientation estimation is done by using multiple ultrasonic sensors at the receiver.

Cricket provides all three forms of location information i.e. space, position, and orientation within a local coordinate system. Cricket achieves a measurement accuracy of 4-5 cm, position accuracy of 10-12 cm and orientation accuracy of 3o-5o. Algorithm for filtering out outlier distance samples also filters out incorrect readings due to ultrasonic noise present in the environment but if source of noise is continuous, Cricket performance is severely degraded.

B. Buzz

A narrowband US indoor positioning system presented in [20] involves design & implementation of two novel systems: Synchronous and Asynchronous BUZZ each having a specific application. Positioning is accomplished by the use of transmission patterns, communicating timing information from infrastructure to the mobile nodes. The channel utilization is maximized by using time division multiplexing scheme. Sync Buzz: Beacons Connected to a central control unit by wires to provide synchronization which makes it unsuitable for certain applications. An extended Kalman filter in used for positioning and a minimum of four beacon measurements are required. However, there is an inconvenient restriction of placing the mobile device to within a specific location at start up. With respect to accuracy, it measures 3D location with accuracy of 4 cm, 50% of the times and 10 cm for 95% of the time. Its update rate is 33 Hz. A Sync Buzz: control of signal transmission is not done centrally. Signals transmission based on internal clock of each beacon and is aimed for applications that do not require high accuracy. It provides position estimates within 50 cm of accuracy, where most estimates are accurate to around 20 cm. Advantages offered by BUZZ are less component cost, low power consumption, improved form factor. One main reason for BUZZ being less accurate is assumption of speed of sound to be constant. This can produce high errors as speed varies considerably with temperature.

C. Dolphin

Broadband ultrasonic location system implemented by [21] consists of transmitters & receivers referred to as Dolphin units. In order to achieve a high processing gain that allows ranging to be accomplished at a variety of angles and distances, and to add robustness in presence of environmental noise, direct sequence spread spectrum (DSSS) techniques are applied. Previously developed ultrasonic location system have low update rate due channel access constraint in the narrowband systems and that problem has been resolved in Dolphin by CDMA (code division multiple access). Ranging messages used in Dolphin consist of carrier wave of 50 kHz, modulated by Gold code using binary phase shift keying. Length of Gold code is 511 bit applied at rate of 20 kHz yield in ranging message duration of 25 ms. TOF of ranging message is identified at receiver by a peak detection algorithm. Authors have developed two different prototypes systems using Dolphin units; Polled centralized location system and privacy oriented location system. In polled, centralized system, transmitters are told when to send ranging messages and a central service collects the TOF data and estimated location of tags. Test of this system was performed under different physical circumstances like all units transmitting and in presence of noise but the accuracy remained under 2.3 cm for all circumstances even though location algorithm returned fewer reading in presence of noise. The authors have also tested Dolphin as privacy oriented location system in both synchronous and asynchronous modes. Synchronous systems have to receive a wireless synchronization signal that an asynchronous system do not need but a disadvantage of asynchronous system is that they need one more signal TOA reading in order to estimate location correctly than in a synchronous system. For 95% of cases, the synchronous system obtains 3D location of mobile unit with an accuracy of 5 cm whereas asynchronous system is much worse with over 25 cm.

D. Robust Broadband ultrasonic location and orientation estimation

A very robust broadband us location system presented in [22] provides a very precise location and orientation estimate. It is the first system that uses frequency hopped spread spectrum (FHSS) and provides a comparison with DSSS. The architecture consists of a number of fixed nodes at known position called base stations (BSs) and mobile nodes (MDs) whose location and orientation is to be estimated. An RF synchronization is provided between the BSs and MDs which determines delay between received and transmitted signal and measure TOF accurately which can be converted to absolute distances. MDs process received US signals to find TOF and AOA using a uniform circular array of transducers. The problem of orientation estimation is addressed by use of array signal processing and modal-decomposition acoustic theory is applied for AOA estimation. Spread Spectrum (SS) modulation scheme not only provides robustness to multipath and noise but also allows multiple access simultaneously, thus increasing update rate which in turn increases accuracy. The system is tested by using DSSS and FHSS and comparing the accuracy and robustness. The variable carrier frequency offers one major advantage of FHSS that the noise and multipath in the same band of frequencies affects it. Data signal generated using Kasami orthogonal code and carrier is modulated using BPSK allowing an efficient use of bandwidth. Similarity between received signal and expected signal give TOF estimation and a broadband AOA estimation procedure is employed. Fast Fourier transform (FFT) of received signal at each sensor is computed and AOA estimate is calculated using UCA-RB-MUSIC algorithm. Results show that FHSS has far better accuracy than DSSS. The 3D location estimated by prototype using FHSS provides estimation accuracy of less than 1.5 cm for 95% of the cases which is the best location estimation by an ultrasonic location system.

E. Indoor localization system employing CDMA

A novel indoor ultrasonic locating system [23] has been presented that uses CDMA and provides fine-grained location estimates. The DS-CDMA scheme provides robustness to the system in noisy indoor environment. TOA measurements of ultrasonic signals are calculated and these ultrasonic signals consist of BPSK modulated Gold codes. The system is centralized and a central PC is responsible for control and performing computations based on observed values. Distance is estimated by TOA of ultrasonic signals and location estimation is performed using trilateration. The hardware complexity and size of nodes is reduced as all the computations and processing and control is performed by the central PC unit and all the nodes are synchronized. In the experiments performed, four transmitters are attached to the ceiling and four distinct Gold codes are generated and assigned to each of them. Four distance samples are computed but for trilateration, 3 samples are enough for location estimation. So either the value with minimum value of peak correlations is eliminated or 4 combinations of the 3 values are used to compute 4 location estimates and center point of these 4 estimates is calculated as final. The results indicate accuracy of 2 cm for 99% of time on ground plane and same accuracy 95% of the time when mobile node is higher than the ground plane and near the ceiling. However, all the experiments are performed in a noise free environment and the above accuracy figures may reduce as in real indoor environment the ultrasonic noise is very prominent. Also the hardware of the nodes is not optimized and nodes can be bulky which is also not desirable from practical point of view. For location estimation, 2 methods are proposed.

V. CONCLUSIONS

In the present time of smart technologies, positioning information is needed by many different applications. Each application has different requirements and many different locations systems have been developed each serving certain specific needs along with many advantage and limitations.

In this article, we have described basic concept of indoor location estimation, familiarized various techniques present in the literature employed for this purpose. Besides infrared and vision based systems, most of indoor location systems use RF and Ultrasonic signals for providing location and orientation information. We have given a brief overview of RF systems and described how various properties of RF signals have been

Table 1: Comparison of US systems Reviewed

System	Spreading and Channel access	update rate	Measurement method	Accuracy (cm)	Orientation (degrees)	Structure	Cost
Cricket	-	Low (1 Hz)	TDOA	10 cm	3-5	Decentralized	Low
Buzz	-	High (33 Hz)	TOA	4-10 cm	Not supported	Centralized, decentralized	Low
Dolphin	Gold Codes / CDMA	High (20 Hz)	TOA	3 cm	Not supported	Centralized	Medium
D	Kasami codes FHSS	High	TOA, AOA	1.5 cm	4.5	Centralized	High
E	Gold Codes / CDMA	High	TOA	2 cm	Not supported	Centralized	

utilized for location estimation. Later, we have reviewed ultrasonic systems. US location systems provide fine-grained location estimation and overall cost of such systems is comparatively low. Each system requires deployment of infrastructure in a certain building to be able to provide location of mobile nodes.

However, a major challenge for both RF and US location system is the harsh nature of indoor environment. Noise, multipath propagation of RF and US signals and lack of LOS results in erroneous location estimates. These limitations have been addressed in many location systems and have been able to successfully reduce their impact. US systems are more prone to US noise which is present indoors. Techniques have been developed to mitigate its effect but a permanent source of noise may still degrade system performance severely. There exists no system that can address all needs and advantages and each system has different application area depending upon its accuracy, update rate, scalability and cost.

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