Comparative Assessment of Indoor Positioning Technologies, Techniques, and Algorithms

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***Abstract*—Indoor positioning systems (IPS) are used to locate the position of objects in indoor environments. Due to its many real-world applications, IPS has garnered interest from both academia and industry. Each IPS is made up of three major components: sensor technology, position-finding technique, and operating algorithm. The goal of this paper is to examine and independently compare different types of components with the aim to understand and make useful suggestions for improvement. This paper also presents the past and current trends in IPS and predict the future trends in approaches to the design and implementation of IPS.**

Keywords—IPS, positioning techniques, positioning technologies, algorithms, scene analysis

I. Introduction

Indoor positioning systems (IPS) are combinations of methods and technologies used to locate the position of objects in indoor spaces [1]. Due to their wide application, IPS have garnered tremendous interest from both science and industry. The demand for IPS technologies is fueled not only by the inability of conventional satellites to penetrate walls and other obstacles, making them unusable in indoor environments, but also the advent of mobile devices such as the smartphone [2], [3]. Furthermore, the creation of IPS technologies has contributed immensely to automation and control industries, robotic guidance, and real-time tracking.

A. Indoor Positioning Technologies

Nine IPS technologies were considered in the preparation of this paper: infrared (IR), ultrasound, audible sound, magnetic, optical and vision, radio frequency (RF), visible light (VL), dead reckoning, and hybrid systems. Later in this paper, each of these technologies are analyzed and the challenges and drawbacks of such a system identified.

B. Indoor Positioning Technique

Although various indoor positioning (IP) techniques are available in the market, only four most common methods are analyzed, compared, and discussed in this paper: triangulation, trilateration, proximity, and scene analysis/fingerprinting.

C. Indoor Positioning Algorithm

Four major algorithms have been adopted for IPS: time of arrival (TOA), time difference of arrival (TDOA), angle of arrival (AOA), and received signal strength (RSS)/received signal strength indicator (RSSI); as discussed in the following sections.

D. Performance Metrics

The metrics used to evaluate IPS technologies are examined, starting with a clear definition of: accuracy, availability coverage area, scalability, cost, and privacy.

E. Trends and Conclusion

After carefully analysing the IPS and discussing the past and present trends, the future trends are speculated.

II. Indoor Positioning Technologies

Different IP technologies are discussed in this section, including its respective challenges and drawbacks; a summary can be found in Table I.

A. Infrared

Active badge, the most common type of infrared (IR) tracking, is used to determine the position of objects using a badge or other identifying hardware attached to the object of interest. Improved IPS have been proposed that use passive thermal IR sensors, called thermopiles [4]. Systems of this type are composed of linked IR sensors connected to a server [5], [6].

Even though IR systems have relatively low implementation costs, they offer limited coverage range and accuracy [7]. A substantial number of receivers are required to improve their accuracy [5], leading to a higher cost of implementation. IR has also been associated with line of sight (LOS) problems. LOS can be blocked between sender and receiver by interference from fluorescence light fixtures or even sunlight. These issues have limited the use of this technology [5].

B. Ultrasound

This technology uses ultrasonic tags attached to objects. These tags play the role of transmitters or receivers [8], [9]. Like IR, ultrasound has high accuracy at low range, making it ideal for use indoor environment. While some ultrasound systems use narrowband signals, others utilize broadband, which offers higher accuracy [10].

The Cricket [11], Active Bat [12], and Dolphin [13], [14] systems are among the most common IPS that use ultrasound technology. The major challenges of this technology are its relatively slow signal speed, its low penetration strength through walls, and the fact that its accuracy is greatly influenced by path interference, such as noise, sunlight, etc., which all contribute to a reduction in precision and performance.

TABLE I. SUMMARY OF IPS TECHNOLOGIES

Technology	Technique	Algorithm	Pros	Cons
Infrared	Trilateration	TOA, TDOA	Low cost, medium accuracy, real-time	Complex, low accuracy
Magnetic	Triangulation	AOA, TOA	Real time, high accuracy	High cost, complex, low privacy
Optical and vision	Scene analysis and proximity	RSSI	Real time	Low scalability, medium cost, low privacy and accuracy
Audible sound	Trilateration	TOA	Medium accuracy and cost, real time	Low privacy, complex, medium scalability
Ultrasound	Trilateration and Triangulation	TOA, TDOA, AOA	Medium accuracy, low to medium cost, real time	Low privacy, medium complexity
Radio frequency	Trilateration, fingerprinting and Proximity	TDOA, TOA, RSSI	Real-time, high scalability	Low privacy and accuracy, high cost and complexity.
Visible light	Triangulation and trilateration	AOA, TDOA, RSSI	High accuracy, low cost, high scalability, high privacy, real-time	Limited conditions for application

C. Audible Sound

Audible sound has a much wider coverage range than ultrasound and infrared [14]. This technology uses audible sound waves to locate the position of objects or people indoors [5], [15]. The most common examples of this technology are Beep, BeepBeep, and Guoguo [16].

Audible sound technology avoids some of the challenges faced by ultrasound and IR, providing higher accuracy at a lower cost [17]. However, systems of this type require many sensors to be deployed for high accuracy. In addition, audible sound technology is also affected by interference, e.g. exogenous noise and reflection. Furthermore, its low penetration—due to its use of sound waves—and intrusive nature makes audible sound less efficient in areas with many disruptions [18].

D. Magnetic

The magnetic method is a well-established technology used to determine object position and for tracking [19]. This method estimates the position of objects or people through careful measurement and analysis of the magnetic fields of the Earth [18].

Even though this method has a very high accuracy and is immune to non-line of sight (NLOS) errors, it has a limited coverage range [17], [20]–[22]. This singular drawback makes magnetic technology a less efficient and less robust system. If this drawback is to be eliminated, more magnetic sensors are required, which increases the cost and complexity of setting up such a system [17], [22]. This method is inappropriate for use in tall buildings or the interior of metal structures [22].

E. Optical and Vision

In this technology, the position of an object or person is determined by using a marker or image that is within the line of sight of a camera or mobile sensor [21], [23]. Examples of markers used include barcodes, fiducials, and QR codes. Two common applications of this type of positioning are marker-based and augmented reality. Even though this positioning technology has a relatively low cost, this comes at the expense of reduced accuracy [24]. Like most technologies, it is greatly influenced by the presence of interfering light, prone to accumulative errors, and has an inherent lack of privacy. In general, it offers poor performance [23], [25].

F. Radio Frequency

As its name implies, this technology utilizes radio frequencies (RF) to obtain the position of an object or person and can be effective for tracking and navigation [1]. Perhaps the greatest advantage is its high penetration strength through walls. Its most common types include Bluetooth devices, server, WLAN, and Bluetooth sensors [3], [18].

Each RF type has its own problems however, in general, RF technologies are prone to disturbances such as electronic, storms, and even organic matters. It exhibits the properties of propagated waves such as absorption, interference, attenuation, and reflection, which can cause degradation or a total loss of signal at the receiver. All of these features combine to make RF a low-performing and inaccurate positioning technology.

G. Visible Light

This method uses visible light to transmit data at wavelengths between 380–780nm [17]. The light is propagated using compact fluorescent and LED lamps that are capable of transmitting data at the rates of about 10 kB/s to 500 MB/s [25], [26].

Its disadvantages include complex design, especially when used for wide coverage; the use of this type of system for wide coverage also increases its cost. It can only be used in well-lit areas, and is mostly seen as an alternative when other technologies are not effective [25], [27], [28].

H. Dead Reckoning

Also known as pedestrian dead reckoning (PDR), dead reckoning predicts future positions of moving objects given their current position and speed, previous positions, and time spent at each position [29]–[31]. This method is especially applicable when the use of radio frequency and visual technologies is impossible [29].

Even though this method typically has high accuracy with first predictions, its accuracy dwindles over time due to accumulated errors [30], [31]. However, its accuracy can be greatly improved when used in conjunction with other methods, as suggested by [32], at the expense of increased complexity and cost. Its advantages include low cost, high simplicity, and good real-time accuracy.

I. Hybrid

As the name implies, it is the combination of two or more of the technologies discussed in sections A–I. A typical example is the Critical system, which incorporates both ultrasound and RF technology [43], [44]. This method aims to use the strengths of one technology to mitigate the weakness of another. As can be inferred, a combination of these technologies gives the hybrid positioning system higher accuracy, performance, and usability. Its major drawback, however, is that due to its combination of technologies both the complexity and cost of the system increase.

III. Indoor Positioning Techniques

Four different IP techniques are discussed and compared in this section. Table II summarizes the advantages and drawback of each of these techniques; it can be observed that most IP techniques can provide high accuracy, albeit at an increased cost.

A. Triangulation

Triangulation is a positioning technique that uses the geometric properties of triangles to determine the location of a target object; angles between two known reference points are calculated [1]. This technique is based on direction-finding, which involves using intersection of two-line angles to estimate the position of an object under consideration [1], [3]. The distance between these two-line angles and the target object is computed using an angle of arrival algorithm [3]. The position of the target object is obtained by computing the position of the transmitter, given its angle and distance to the reference points used [2].

Some have posited that the use of reference points to determine position is a simple and low-cost approach; however, caution must be used when using multiple reference points to avoid errors and loss of accuracy [17]. Furthermore, when the area to be covered is larger, the hardware required for triangulation tends to be more complex and expensive.

B. Trilateration

Trilateration, like triangulation, also uses the geometric properties of triangles to estimate the location of target objects [3], [35]. However, unlike its counterpart, this method uses the distance between the reference points and the target object to determine the location of the target object [1], [2]. Multilateration, a variant of trilateration, involves the use of four or more reference points [5]—hence the prefix ‘multi’.

Unlike triangulation, the time of arrival (TOA) algorithm is used to determine the location of the target object; the time it take for the signal to be received from the transmitter is used to determine the distance from that transmitter to the reference point [26].

A recent improvement on trilateration is the introduction of time difference of arrival (TDOA). Unlike the TOA, this method estimates the position of the transmitter by determining the difference between the TOA at the two receivers [36]. This has the advantage of providing higher accuracy; however, it requires more expensive hardware and certain environmental conditions can greatly reduce its accuracy [35].

TABLE II. SUMMARY OF IPS TECHNIQUES

Positioning Techniques	**Algorithms**	**Advantages**	**Drawback**
Triangulation	AOA	Less complex, low cost, and high accuracy at low coverage range	Complex, expensive, with low accuracy at wider coverage range
Trilateration	TOA/TDOA	High accuracy	Complex and expensive
Proximity	RSSI	High accuracy	Complex and expensive
Scene Analysis/ Fingerprinting	RSSI	High performance	Complex, expensive, medium accuracy, time consuming

C. Proximity

Unlike triangulation and trilateration, proximity only provides information about position, not an absolute or relative position [3], [17]. Commonly used in models that utilize radio frequency, the information is provided through a grid of antennas situated at known positions to determine the unknown position [3], [26]. The mobile device’s position is obtained from the closest antenna. However, if the device is detected by two or more antennas, its position is computed using the location with the strongest signal [17], [26]. An RSSI algorithm is used to obtain information on the positions of target objects [36].

Proximity is best used in location-based services or device tracking and navigation [17]. However, it is also used in systems that uses Bluetooth, IR, RFID, etc., because it requires little to no calibration [17], [30]. A major setback of the proximity technique is that it requires a large spread of readers to cover wider areas [30]. This requirement makes it more expensive and more complex to use in large areas.

D. Scene Analysis/Fingerprinting

This method locates positions not with angles or distances but by obtaining and analyzing data or features obtained from scenes. It uses these data to estimate the position of the target object by comparing it with the information in its existing database [3], [26].

The information obtained from scenes is referred as a fingerprint. Each fingerprint differs from the other and distinguishes scenes from each other. The process of obtaining information from scene is referred to as fingerprinting or location fingerprinting [3], [5], [37]. Fingerprinting can be done offline or online [3].

This method has the advantage of high accuracy [26], [38]. In online fingerprinting, the information obtained on positions from the grid points is computed from any feasible position [3]. Scene analysis, however, is very time-consuming and has a high computational cost.

IV. Indoor Positioning Algorithms

This section examines four of the major types of algorithm used in indoor positioning. A summary can be found in Table III.

A. *Time of Arrival*

Also referred to as time of flight (TOF), the time of arrival (TOA) algorithm uses the time required to propagate a signal from a transmitter to the receiver to estimate the distance between the two [39]. Unlike time difference of arrival (TDOA), TOA uses absolute time taken [36]. The distances between each reference node to the Access points (APs) is taken while the location of the transmitter is computed using basic geometry.

Despite its high accuracy, TOA, not only requires that the transmitters and receivers be synchronized but also that timestamps should accompany each signal. Furthermore, its efficiency is dependent on the signal bandwidth and sampling. A low sampling rate gives a low-resolution TOF. A large bandwidth gives a high resolution, however, it cannot eliminate the errors caused by an obstruction in the line of sight between the transmitter and the receiver because the signals are deflected along a longer path, thereby increasing the time taken to reach the receiver [11], [26].

B. *Angle of Arrival*

This angle of arrival (AOA) approach calculates the angle and distance between two or more reference points and the target. The angles at which the signal is transmitted are determined by the receiver and measured with the aid of antennae arrays set on the receiver side [2]. The angles and distances are calculated to obtain the location of the transmitter. This method can be very advantageous in navigation and tracking and can be performed with only two monitors in a 2D environment, but for 3D tracking it requires three monitors [39]. On the whole, AOA requires costly hardware and painstaking calibration.

C. *Time Difference of Arrival*

This approach is very similar to the TOA method. It also measures distance of the mobile transmitter; however, in this case, it does so with the time difference of the signal propagated from the transmitter to the known reference points [c]. Just like the TOA, the accuracy of TDOA is dependent on the sampling rate and the line of sight between the transmitters and the receivers. This implies that it has the advantage of not needing the absolute time of propagation, which makes TDOA less complex than TOA. Furthermore, TDOA offers higher accuracy than TOA [36].

TABLE III. SUMMARY OF IPS ALGORITHMS

Algorithm	Measurements	Advantages	Drawbacks
Angle of arrival (AOA)	Angle-based	High Accuracy in small coverage range	Increased complexity, low accuracy and costly at wider coverage.
Time of arrival (TOA)	Measures distance	High accuracy	Increased complexity and cost
Time difference of arrival (TDOA)	Measures distance	High accuracy	Costly
Received signal strength indication-based (RSSI-based)	Measures with signals	Low cost	Medium accuracy

D. *RSSI-Based*

This algorithm uses the RSSI method, and so inherits its disadvantage of being liable to degradation in performance in complex situations. However, it is ideal for simple indoor environments, where it provides good accuracy. It uses two techniques for the location of target objects: the pseudo-range measurement and the trilateration. The pseudo-range measurement approach works by analyzing a radio propagation relationship. Trilateration, however, works with multiple base stations, and is popular for use in locating smartphones from access points [3], [36].

V. PERFORMANCE METRICS FOR IPS

Despite the tremendous contributions to indoor positioning technologies made by many authors over the years, gray areas still remain that must be addressed as the technology matures.

A. *Accuracy*

Accuracy, as defined by the Joint Committee for Guides in Metrology (JCGM), is the closeness of a measured quantity to its true quantity [21]. Accuracy is one of the qualities of these technologies that has improved the most; however, there is still room for improvement. The majority of IPS solutions provide low accuracy at least under some conditions. So far, only visible light and magnetic systems have shown a high level of accuracy. Compromises must be made if the accuracies of these technologies are to be improved satisfactorily [3], [5].

B. *Availability*

The availability of an object is the percentage of time during which the object is available for use at its original accuracy. Availability can be defined at three levels: low availability (object is available less than 95% of the time), regular availability (object is available 99% of the time) and highly available (object is available for use 99.99% of the time) [26]. It is not realistic to expect an object to be available 100% of the time; however, it should be possible to improve IPS to the point that they are highly available.

C. *Coverage Area*

As has been hinted throughout this paper but not previously defined, coverage area refers to the area that can be surveyed by an IPS. Each IPS comes with different coverage range. The wider the range, the more effective the IPS [26].

Coverage range can be classified into three levels: local, scalable, and global [5]. Local coverage refers to the ability of the IPS to cover a specific area, scalable coverage refers to its ability to be improved with additional hardware, while global coverage refers to an unlimited coverage area that is on a global scale. Current IPS should be so improved to surpass 60 meters, as suggested by [26].

D. *Scalability*

As mentioned earlier, the scalability of an IPS is its ability to locate objects in a single room or building, beyond it and worldwide. The IPS developed to date that possess high scalability is done so at the price of increased cost and complexity. There is a need for research to obtain improved scalability at lower cost.

E. Cost

Cost can be monetary, or in terms of requirements of time, energy, or space. A Cost is incurred at different phases of implementation: installation, maintenance, infrastructure acquisition, and acquisition of the positioning devices [3], [40]. IPS that reuse existing infrastructure are usually the most cost effective. Some devices, like RFID tags, are particularly energy conserving and thus may be more cost effective.

F. Privacy

Privacy is a very sensitive area for improvement, as users may be uncomfortable if they feel their positions are being tracked and revealed to unknown individuals. Privacy is also germane for security reasons and involves control over the spread of user information [40]. A major aspect that requires privacy is real-time tracking and navigation, to avoid increased risks of theft, kidnapping, and unwanted intrusion.

VI. Trends and Conclusion

A. Trends in the Development of IPS

1) Past: In the past, the major goal of IPS was to find a technology that suited a particular condition, with less attention paid to improving overall accuracy. In addition, the early prototypes of IPS were generally chosen based on cost effectiveness. The infrastructure required for IPS during this period was very expensive, and their practicality was questionable. Typical examples of early systems include Active Badge [41], Cricket [42], and Active Bat [43].

2) Present: The following trends are noticeable in the development of IPS and may remain relevant for a considerable period:

- Reuse of existing infrastructure: Most IPS use items not originally purchased for their current use. A typical example is the incorporation of access points (APs) or lamps.
- Hybrid positioning system: The recent trend of IPS is to improve existing systems by masking their weaknesses with the strengths of another type of IPS.
- Mobile devices for positioning systems: Recently, mobile devices such as phones have been incorporated in IPS. This allows new features like navigation and real-time tracking.
- Crowdsourcing/open distributed collaboration: Developers of IPS have realized the limitations of innovating alone and have developed effective methods of sharing their advances through crowdsourcing

3) Future: The future cannot be accurately predicted; however, we can speculate:

- There is a strong possibility that future IPS will incorporate both IPS and outdoor positioning systems, making use of such system to locate any person or object, regardless of location, seamlessly. This will be facilitated by the current widespread use of mobile devices like smartphones.
- Much attention is already being centered on improving the privacy of IPS and making such systems more secure. Intentional sharing of location will be added to the privacy feature of IPS [44].

B. Conclusion

In conclusion, by comparing the IPS technologies, some important aspects have been identified:

- Improvement of each technology has offered great additions to the field of IPS design. It can be asserted that no technology is without merit, as each new technology has cleared the way for the advent of a better technology.
- The technique, algorithm, and technology each play a considerable role in improving the accuracy of IPS. For example, incorporating Bluetooth with triangulation can tremendously improve its accuracy.
- Every IPS technology has its own drawbacks and challenges; there is not (yet, at least) any one-size-fits-all technology. Tradeoffs must be made; cost must sometimes be sacrificed for accuracy, and so on.

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