

## Review Article

# Mobile Positioning Techniques and Systems: A Comprehensive Review

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The recent developments in mobile positioning technologies and the increasing demands of ubiquitous computing have significantly contributed to sophisticated positioning applications and services. Position information represents a core element in the human-centred activities, assisting in visualising complex environments effectively and providing a representational coordinate for localisation, tracking, and navigation purposes. The emergence of smartphones has accelerated the development of cutting-edge positioning-based systems since they are contained to have more processing, memory, and battery power. Similarly, mobile devices are now equipped with new sensory capabilities, wireless communications, and localisation technologies. This has quadrupled towards new advances on positioning techniques, enhancing the existing ones and brought more value to positioning-based systems. Research studies in positioning techniques have progressed in different directions, and no work has categorised and assessed the various advancements in this area. Accuracy and precision are the two challenging aspects that are crucial to the proper functioning of a positioning system. In practice, there is not a single positioning technique that could be appropriate for different situations. Most of the survey papers have focussed on carrying out their review on conventional positioning techniques. The common positioning technique uses simple technologies and is applied to a single type of environment. Hybrid techniques are the next generation of positioning technique that is supporting the real and complex environment. This paper presents a comprehensive review on the mobile positioning techniques and systems. A total of 21 positioning systems published between the years 2012 and 2018 in the top 5 most popular indexed databases are reviewed. The positioning techniques are identified and streamlined through a methodical process, and the selected ones are reviewed using derived parameters. This paper provides a significant review of the current state of the mobile positioning techniques and outlines the research issues that require more investigation.

## 1. Introduction

The definition of “positioning” is typically used to express the capability of locating the physical position of an object in a predetermined space [1]. The rise in ubiquitous computing and context-aware information has driven the way of more advanced positioning systems. Besides, the recent developments in wireless technologies have propelled new paradigms of positioning techniques that could be supported in different situations. The application of positioning systems has been appraised in various application fields including navigation, tracking, healthcare, tourism, manufacturing,

and personal security activities [2]. The term “positioning” shares the same concept as “localisation”; however, it is often correlated with real-time characteristics.

The upsurge of positioning systems has generated an enormous amount of awareness among the communities worldwide. The emergence of online social networking (OSN) sites has indirectly pushed for more developments in location-based services (LBS). Recently, Facebook has incorporated a new feature called “Nearby Friend” in their OSN platform, which attracted millions of followers [3]. In the same vein, context-aware systems have taken in a new dimension with the integration of LBS. The recent

positioning techniques have augmented the current context-aware system with new features which have enriched the human capacity to visualise complex environments easier. The exigencies of positioning in the worldly activities have continuously pushed developers to rethink over their conceptual model and bring new additions to the current ones.

The exponential increase of ubiquitous devices and mobile persuasive devices has been pivotal to the enormous developments of LBS applications. Nowadays, smartphones are built with more processing, memory, and battery power. Besides, it is integrated with wireless communications and localisation sensing capabilities, therefore making it more capable of sensing location autonomously without any human intervention. Many existing solutions have used GPS for localisation and tracking purposes, but they present several limitations to work under different environments due to the loss of signals [4]. In addition, GPS consumes substantial energy, thus degrading the user experiences over time [5].

Other works have employed basic positioning techniques such as time of arrival, received signal strength, fingerprinting, or image patterns. Nonetheless, the quest for real-time positioning is not achievable with the above methods since it does not cater for mobility. Most LBS applications have either been implemented on a specific environment, i.e., indoor or outdoor environment. Mobile collaboration applications that use resource positioning require accurate indoor and outdoor locations at the same time. Therefore, there is a need for a seamless positioning service for mobile-context positioning systems. To the best of our knowledge, there is no such seamless positioning solution. This review provides a clear understanding to researchers on the appropriate positioning methods to use.

As an alternate solution, novel positioning techniques, usually known as hybrid or next-generation positioning technique, are being developed from the wireless transceivers and sensors on smartphones. However, there is not a single positioning solution that could be fit in for all situations. It requires the appropriate technique and approach for attaining an acceptable level of accuracy and precision. Different applications may require distinct positioning information with respect to their accuracy, precision, complexity, scalability, cost, and deployment efforts. Many works have opted to compromise energy efficiency for increased accuracy, resulting in another setback in user experiences.

Hybrid techniques are a combination of the known positioning techniques to amplify the existing ones. New positioning solutions are incorporating hybrid techniques to edge themselves in front of their predecessors. In many surveys, positioning metrics are defined to review the techniques, thus providing a limelight on their characteristics. However, there is a lack of research on the recent advances in positioning algorithms and techniques for mobile positioning-based systems. In this paper, recent positioning systems with hybrid positioning techniques are identified and are compared to the defined key metrics providing a better insight into the positioning advances. Initially, a brief introduction of the base techniques is carried

out to understand their functions and prerequisites. Furthermore, this provides a much better insight into the different permutations of the base techniques that could be linked to form hybrid ones.

Proximity, received signal strength (RSS), time, angle of arrival (AoA), sensor, image, and pattern are general categories to classify the base methods for determination positions. Figures 1 and 2 provide a taxonomy of the conventional positioning techniques that could be linked to achieve hybrid ones. The next section is the research methodology. Section 3 gives a brief overview of the recent surveys carried out in this field. Section 4 presents the set of defined key metrics and related challenges. Section 5 compares the base positioning techniques against a set of defined key parameters and related technologies. Section 6 describes, analyses, and assesses the selected positioning systems. Section 7 presents the challenges and research directions. Section 8 provides the conclusion of the study.

## 2. Research Methodology

In this research, the objective is to conduct a methodical review by (1) identifying and enumerating all the positioning algorithms and techniques for mobile positioning-based systems during the last 6 years, (2) a classification model of the techniques, (3) carrying out a comparative study with derived parameters, (4) describing the challenges for each technique, (5) identification of the application areas for the positioning techniques, and (6) identifying future research directions in this area. This survey has been carried out by performing a comprehensive literature review of the existing research papers in the area.

Given the large number of research works carried out in this area, the review has been planned using the following methods:

- (1) Determining the search terms
- (2) Listing and reviewing of positioning systems
- (3) Classification of positioning systems

The research methodology is depicted in Figure 3.

*2.1. Data Sources.* With the recent technological advances in mobile systems, new positioning techniques have been developed. As such, there are some articles available on this subject. Initially, a general exploration is carried out on reputed scientific journals and conference proceedings to shortlist the relevant scientific databases. The highest relevance of indexed papers was found in IEEE Xplore, ACM Digital Library, Springer, ScienceDirect, Elsevier, and ERIC.

*2.2. Search Terms.* The review has been planned by determining the most appropriate search strategy, and the search items used were “positioning techniques,” “localisation,” “system,” “user,” “indoor,” “outdoor,” “algorithms,” “mobile,” “smartphone,” and combination of them. The search was limited to the last 6 years, from 2012 to 2018. The last update was on July 2020.

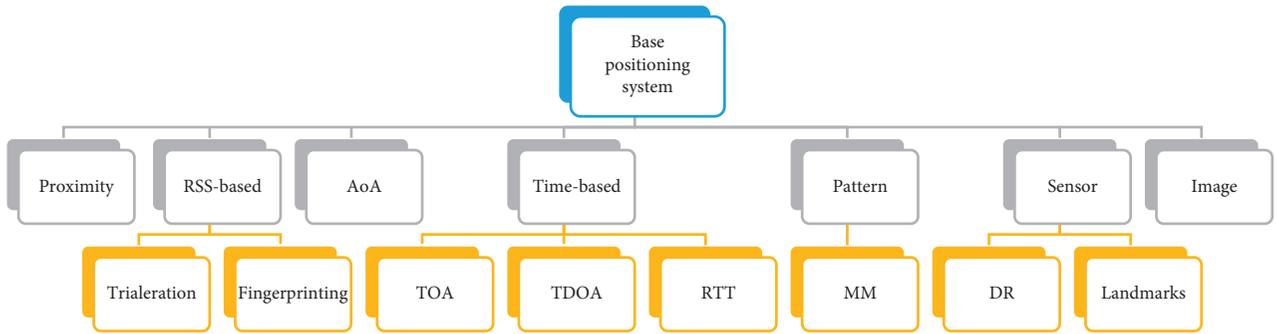


FIGURE 1: Taxonomy of base positioning techniques.

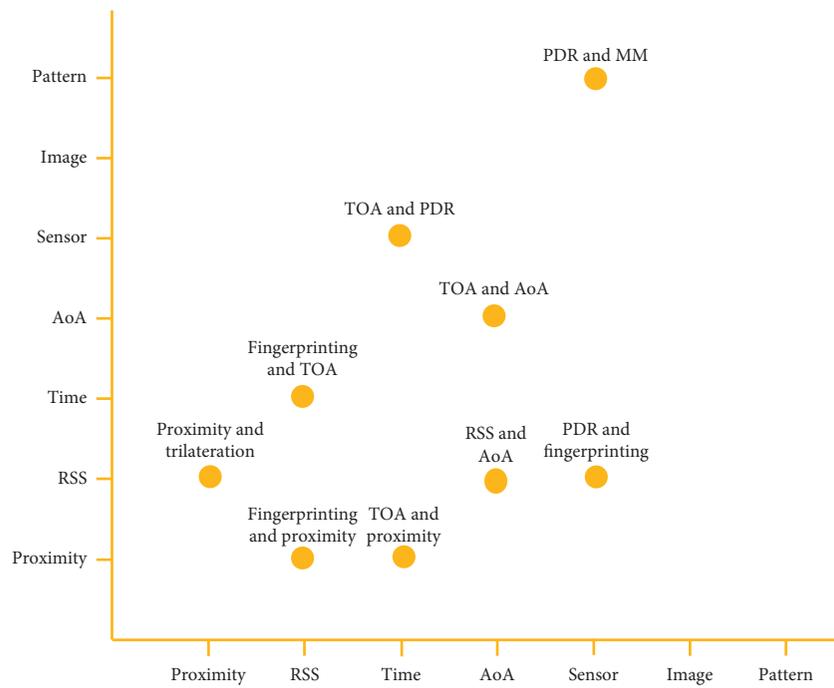


FIGURE 2: Hybrid positioning techniques.

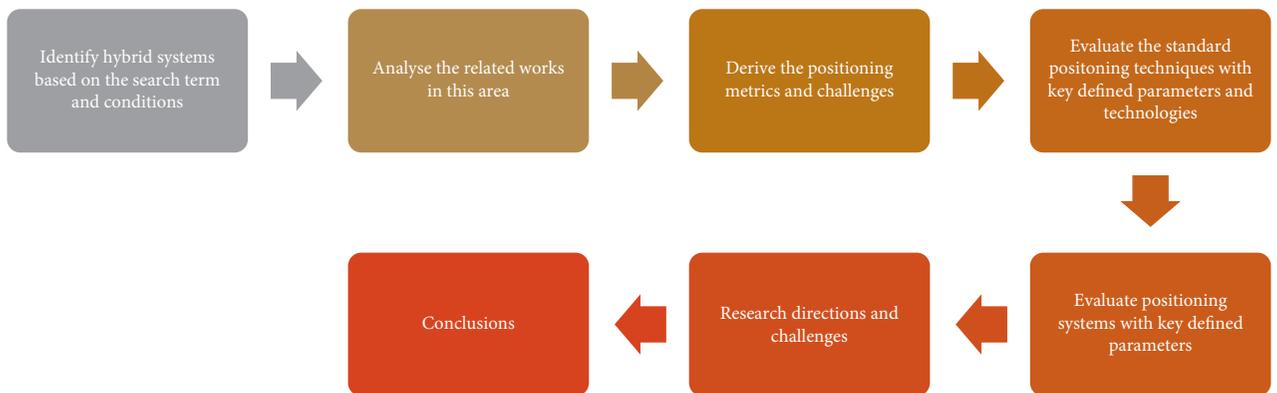


FIGURE 3: Research methodology.

In total, 21 papers were identified and reviewed. The papers were carefully analysed and classified into their specific category.

**2.3. Listing and Reviewing.** The main objective of this survey is to review all the current and promising positioning techniques for mobile systems and assess their performance in different real-life situations. A number of positioning systems by order of relevance to the field of study have been selected and reviewed. Figure 2 provides an insight into the hybrid positioning techniques that positioning systems are currently adapting to provide a better service.

Figure 2 provides an insight into the hybrid techniques that should be studied and evaluated to help researchers and application developers to better understand their application in different environmental scenarios. Each technique uses specific technology or algorithm, and thus, the methods work differently in different situations. Therefore, an understanding of these differences is essential before its selection and application.

**2.4. Classification of Positioning Systems.** In Section 2.3, a 2D perspective of the positioning techniques is presented providing a notion on the different combinations of techniques that can be derived. The techniques have been used for the implementation of recent positioning systems. Table 1 provides a list of the systems classified by their respective techniques, technologies, and application domains.

From Table 1, the percentage of the works implemented in the year 2018 is 29%. In addition, the PDR combined techniques represent around 62% of the total works. The figures can be explained by the fact of the increasing number of smartphones and the technological developments in sensory-equipped devices. Moreover, most of the systems are classified as “research” oriented because they still require a deep level of understanding and investigation before they can be available to the public.

### 3. Related Works

There have been a few survey papers that have carried out a review on the positioning techniques and systems (such as Tariq et al. [24], Al-Ammar et al. [25], Chowdhury et al. [26], Tahat et al. [27], Vo and De [28], Xiao et al. [29], Palipana et al. [30], Maghdid et al. [31], and Moreno and Ochoa [32]). Tariq et al. [24] concentrated their study on non-Global Positioning System (GPS) localisation systems for indoor environments. The authors conducted a comprehensive review of the different techniques and technologies against multiple performance metrics. Besides, they also presented a detailed categorisation of the positioning systems in terms of the techniques employed, technologies, performance metrics, and limitations.

Al-Ammar et al. [25] presented a survey on a comparative study of indoor positioning, technologies, techniques, and algorithms. The standard techniques have been assessed individually together with their respective research gap analysis and limitations. Besides, this work has also

analysed the impact on privacy which is a novel comparison among the recent surveys studied. Though the article has been published recently, the authors have not discussed the latest advances in positioning techniques, i.e., hybrid techniques.

Chowdhury et al. [26] surveyed the latest advances on localisation techniques for wireless sensor networks. In this paper, the recent advances in localisation techniques are detailed based on some known parameters such as processing (central or distributed), transmission range, mobility, operating environment, and node density. A systematic comparison and evaluation of the localisation algorithms have been carried out. However, there is a lack of focus on the wide ranging of hybrid techniques that have assisted the recent developments in the positioning field.

Tahat et al. [27] studied the recent advances in wireless positioning techniques for moving devices. A comprehensive review of the base techniques has been discussed, and the underlying algorithms related to the methods have been reviewed with defined key metrics. The authors concentrated on both indoor and outdoor environments which slightly differs their studies, among others. The study has concluded that there is no single algorithm that could be suited for all types of situations; it is also noted that there is an absence of discussion on hybrid localisation techniques. Vo and De [28] presented a survey on fingerprint-based outdoor localisation. Such techniques were solely concentrated on the indoor environment. The availability of short-range communication infrastructure (Wi-Fi and BLE) is readily present in an indoor environment, thus making it more practical to implement fingerprint techniques. The study concluded that the emergence of sensory devices in smartphone devices can further enhance the fingerprinting techniques. Even so, the techniques are highly effective, but it is very costly to implement. In addition, a comparison with nonfingerprint techniques would have provided a broader picture of the type of environment to use in different scenarios.

Xiao et al. [29] have carried out a comparison on wireless indoor localisation from the device perspective. In this work, localisation has been classified mainly into twofolds: device-based and device-free. These categories were further expanded with all the keynotes such as comparison of existing systems, segregation of application areas, and the respective infrastructure. Nonetheless, the paper did not provide much detail on the recent advances in positioning systems for mobile-based. Palipana et al. [30] have provided further insight on the passive device-free localisation based on radio frequency (RF). The authors have decomposed the localisation dimensions into occupants, space, and time, which are new parameters. However, this survey is only limited to RF infrastructure and indoor environment.

Maghdid et al. [31] presented a survey on the implementation and challenges of seamless outdoor-indoor localisation on smartphones. The study compared various systems with the same characteristics (outdoor and indoor) along with their own techniques and technologies. In another perspective, the paper has analysed outdated systems and has lacked depth in explaining the emerging trends in

TABLE 1: List of systems.

Systems	Techniques	Technologies	Architecture	Application domains
Kumar et al. [6] Liu et al. [7] HimLoc [8] Mashuk et al. [9] Gomes et al. [10]	PDR + fingerprinting	Wi-Fi Wi-Fi Wi-Fi Wi-Fi and Bluetooth (BLE) Wi-Fi, BLE	Central network-based Distributed network-based	Augmented reality Research Research Research Navigation
REFIRE [11] Nazemzadeh et al. [12] Wang et al. [13] Zhou et al. [14]	PDR + trilateration	RFID RFID RFID Wi-Fi	Device-free —	Tracking Tracking Research Research
Kok et al. [15] Marton et al. [16]	TOA + PDR	UWB Ultrasound	Network-based (central)	Research Research
Anisetti et al. [35]	Fingerprinting + MM	Cellular	Distributed network-based	Research
Khalifa and Hassan [17] Qian et al. [18]	PDR + MM	— —	Device-free	Research Research
Kolakowski [19] Crescendo [36] Satan and Toth [20]	Proximity + trilateration	BLE + laser sensors Cellular Bluetooth	Network-based	Research Research Research
Prince and Little [37] Tomic et al. [21] Tang et al. [22]	AoA + proximity AoA + trilateration AoA + trilateration + proximity	Wi-Fi + light sensor Wireless sensor networks Cellular	Central network-based	Research Research Disaster monitoring
Kumarasiri et al. [23]	TDOA + trilateration	Wi-Fi, cellular, and wireless sensor networks	Distributed network-based	Research

positioning techniques. Moreno and Ochoa [32] carried out a survey on the resource positioning methods that support mobile collaboration. The work is quite similar to Maghdid et al. [31], but they have only concentrated on comparing the common techniques based on performance metrics. Table 2 provides an insight of the related works discussed.

#### 4. Positioning Metrics and Challenges

In the above sections, an overview of the recent mobile-based positioning systems has been presented and categorised, respectively, with the associated positioning techniques. In this section, a number of criteria are derived to carry out a systematic assessment of the positioning techniques. The techniques are compared with a focus on mobile technologies while most of the comparison carried out in existing literature studies focussed on general positioning techniques. Each of the metrics identified for the evaluation is explained below.

In this work, the term “accuracy” is defined as the shortest Euclidean distance between the estimated locations and the exact locations, meaning the shorter the distance is, the higher the accuracy is. In most cases, accuracy is a core factor while designing positioning systems; however, a proper trade-off should be devised to harmonise accuracy and other positioning parameters.

“Precision” is the second most important parameter considered in this review, and it determines the regularity of estimations of the specific techniques. A lower precision denoted as “L” states that the percentage of precision is lower than 70%, and a medium precision denoted as “M” states that the rate of precision is lower than 85% and greater than

70%. A higher precision denoted as “H” indicates that the precision is higher than 85%.

The third parameter is “computational load;” it is the measure of the energy consumption for the determination of the position of an object by a particular technique. A high computational load represented as “H” means that the resource consumption is extensive, a medium computational load represented as “M” means that the value is just above average, and lastly, a low computational load represented as “L” means that the energy consumption is reasonably acceptable.

The fourth parameter is “scalability,” and it evaluates the workability of the technique under changing operating conditions. A low scalability marked as “L” signifies that the technique is poorly scalable, a medium scalability marked as “M” means that the technique is scalable to some extent only whereas a higher scalability marked as “H” signifies that the technique is very scalable.

“Flexibility” is the fifth parameter used to assess the performance of the positioning techniques in varying environmental (physical) contexts, i.e., the accuracy and precision of the techniques must have a trade-off value in dynamic environments (indoor or outdoor) so that it can work uniformly. A low flexibility marked as “L” denotes that the technique does not cope well under different environmental contexts. A note of “M” signifies that the techniques can provide a reasonable position value, but it does not work in all spaces. Lastly, “H” means that the technique can operate with the same set of level of accuracy and precision under different environments contexts.

“Centralised and Distributed Processing” is an important metric to evaluate the performance of positioning

TABLE 2: List of surveys.

Survey works	Focus	Performance measurement	Coverage area	Hybrid positioning
Tariq et al. [24]	Base techniques and fusion of base techniques	Positioning metrics	Indoor	Extensive
Al-Ammar et al. [25]	Base techniques	Positioning metrics	Indoor	No
Chowdhury et al. [26]	Positioning for moving devices	Comparison of algorithms	—	—
Tahat et al. [27]	Wireless position techniques	Comparison of techniques	Indoor and outdoor	Limited
Vo and De [28]	Fingerprinting	Comparison of systems	Outdoor	Limited
Xiao et al. [29]	Device-based and device-free positioning	—	Indoor	Limited
Palipana et al. [30]	Radio frequency	Comparison of technologies	Indoor	No
Maghdid et al. [31]	Common positioning techniques	Comparison of systems	Indoor and outdoor	Limited
Moreno and Ochoa [32]	Common positioning techniques	Positioning metrics	Indoor and outdoor	No

techniques. Centralised computing can process the inputs from various nodes independently and can achieve a faster result but with the expense of having a single point of failure. Distributed processing can cooperate with the sensor network nodes and can work autonomously to process the result. However, processing time in distributed computing might be slower and can cause detriment to the seamless positioning results. Centralised processing is marked as “C,” and distributed processing is marked as “D.”

“Heterogeneity” of a positioning technique is a crucial aspect to assess the ability to operate under different hardware characteristics (make, model, and specifications), i.e., different devices, different platforms, different memory sizes, and different processing powers. For example, device heterogeneity is a major challenge that is faced by developers in the domain that should be taken into account while designing the technique. The results might be overlapped with varying technologies and could lead to errors. An “H” means that the technique is heterogeneous and “NH” is nonheterogeneous.

“Orientation” is another important parameter that considers the users’ field of view to calculate the relative position of an object. The more acute the angle is, the more accurate is the positioning result. In application areas such as navigation and tracking, entertainment, and augmented reality systems, orientation is critical. Orientation can be determined using the sensors from mobile phones. However, the challenges of using sensors’ data are the high consumption of energies.

“Trajectory” is also known as the pattern of movement. The movement of the users is taken into account while processing the next positioning result. It can also connect the users’ location points and can derive a pattern so that the system can reuse the same for prediction purposes. In many entertainment services where positioning is applied, the trajectory is used to propose the next point of interests based on the previous location positions, thus keeping the users highly interacted.

Table 3 provides a summing up of the identified positioning metrics. The “importance” of each metric is derived based on our understandings in this field. In this study, “importance” is associated with the amount of significance it has in measuring and evaluating a positioning technique. Finally, the “measure” field provides a quantification of the evaluation of the positioning metrics in their respective dimension.

Table 4 shows a parameter matrix which assesses the key defined parameters with each other. At first glance, Table 4

provides a mapping of the positioning metrics with each other to highlight the connectedness between them. Moreover, the implementation challenges associated with the positioning metrics can also be derived, and an estimated trade-off value can be originated for each parameter.

From Table 4, it gives a clear indication of the related challenges for implementing a mobile positioning system. The trade-offs between the parameters are explicitly described accordingly. For a best-fit situation, all the parameters should function at their optimum level. However, it is not the case for a working situation. As per Table 4, it can be noted that “Load” is critical since it is associated with all the listed parameters except heterogeneity. Load is mostly related to longevity, and it is of paramount importance in a mobile system because it allows for longer user experiences, thus increasing engagement towards these systems. Accuracy and precision are the runners up among in the matrix table, but it is often correlated as the most crucial positioning metrics for a mobile positioning system. Scalability has a direct influence on flexibility, as such techniques are required to work optimally irrespective of the environmental context. Flexibility takes into account the load of the techniques to provide constant positioning information in different environmental contexts. CD processing eventually impacts the load of the mobile device. The processing can either be centralised or distributed. Adding orientation and trajectory will not only enhance the accuracy but will improve the precision. In other words, these parameters enhance understanding of complex environment easier. The next section will provide a detailed review of the positioning techniques with the defined key metrics.

## 5. Review of Positioning Techniques

The main contribution of this work is to review all the current and promising mobile positioning techniques and assess their performance in different real-life situations. First, an initial understanding of the common positioning techniques is required. Next, a number of positioning techniques by order of relevance to the field of study have been carefully selected and reviewed. We describe the common positioning techniques that have identified and selected for investigation in Table 5. A detailed review of the positioning techniques is carried out in Tables 6 and 7. The techniques are methodically analysed and compared with

TABLE 3: List of positioning metrics.

#	Metrics	Importance	Measure
1	Accuracy	Critical	cm, m, or km
2	Precision	Critical	High (H), medium (M), low (L)
3	Computational load	Critical	High (H), medium (M), low (L)
4	Scalability	High	High (H), medium (M), low (L)
5	Orientation	High	Yes (Y) or no (N)
6	Flexibility	Low	High (H), medium (M), low (L)
7	Centralised or distributed computing	Low	High (H), medium (M), low (L)
8	Heterogeneity	Low	H: heterogeneous, NH: not heterogeneous
9	Trajectory	Low	Yes (Y) or no (N)

TABLE 4: Parameter matrix.

	Parameters									
	Accuracy	Precision	Load	Scalability	Flexibility	CD processing	Heterogeneity	Orientation	Trajectory	
Accuracy	—	—	Y	Y	—	Y	—	Y	Y	
Precision	—	—	Y	Y	—	Y	Y	Y	Y	
Load	Y	Y	—	Y	—	Y	—	Y	Y	
Scalability	Y	Y	Y	—	Y	—	Y	—	—	
Orientation	Y	Y	Y	—	—	—	—	—	—	
Flexibility	—	—	Y	Y	—	—	—	—	—	
CD processing	Y	Y	Y	—	—	—	—	—	—	
Heterogeneity	—	—	—	Y	Y	—	—	—	—	
Trajectory	Y	Y	Y	—	—	—	—	—	—	

TABLE 5: List of positioning techniques.

Category	Description	Techniques
Proximity	The closest objects are collocated with the base station	Cell ID
		Cell ID with sectors
		Cell ID with TA or RSS
		Cell ID with sectors or TA or RSS
RSS	The RSS is measured and then translated into a coordinate system	Trilateration
		Fingerprinting
		TOA
Time	The measured time of the signal propagation is converted into the relative distance	RTT
		TDOA
		Triangulation
Angle of arrival	The incident angle of the signal wave is measured and then computed to find the location of the receiver	Triangulation
Sensor	Take the readings of inertial sensors from smartphones to find the position of user	Dead reckoning
		Identification of landmarks

the selected metrics and respective technologies, thus deriving a comprehensive research gap analysis. The analysis and comparison are performed with a key focus on the recent breakthrough in mobile technologies.

Proximity-based technique is a simple localisation method, as the term expresses “proximity,” it detects the closest objects that are collocated to a base station (BS). The techniques usually employ a series of detectors, each having a known position. In a mobile cellular network scenario, the detectors can be categorised as BS; the location of the device is estimated by determining the BS the device is connected [38, 39]. The proximity-based category comprises of four techniques: cell ID, cell ID with sectors, cell ID with TA or RSS, and cell ID with sectors or TA or RSS. Cell ID uses mobile cellular network to identify the approximate position

of a mobile handset by predetermining the BS it is connected. The coverage area is defined with respect to the cell radius, and the location of the mobile phone is estimated within that radius. In cell ID with sectors, the cell is divided into sectors, and the BS employs directional antennas that cover each of the allocated sectors. The cell ID with time advance (TA) considers the time factor, and it calculates the length of time of the signal to reach the BS from the mobile phone. Cell ID with sectors + TA or RSS includes clustering of the cell into sectors, and it uses TA or RSS values to estimate the location of the mobile device [27, 31, 40].

Received signal strength (RSS) technique is an anticipated research area that many researchers are digging into to extend the localisation technique domain. In a wireless local area network (WLAN) context, the location of a mobile device is

TABLE 6: Comparison of positioning techniques with key defined parameters.

Techniques	Parameters										
	Accuracy		Precision	Load	Scalability	Flexibility	CD processing	Heterogeneity	Orientation	Trajectory	
	Indoor	Outdoor									
Proximity	Cell ID	Room scale	Cell size(CS)	L	L	H	M	C	H	—	—
	Cell ID with sectors	—	Sector size (SS)	—	L	H	M	C	H	—	—
	Cell ID with TA or RSS	—	(CS/4)	—	L	H	M	C	H	—	—
	Cell ID with sectors or TA or RSS	—	(SS/4)	—	L	H	M	C	H	—	—
RSS	Trilateration	—	≤30 m	L	M	M	L	C or D	NH	—	—
	Fingerprinting	≤9 m	—	H	M	L	L	C	NH	—	Y
Time	TOA	≤15 m	≤300 m	H	L	H	L	C	—	—	—
	RTT	—	≤180 m	H	L	M	L	C	—	—	—
	TDOA	≤5 m	≤150 m	H	L	M	L	C	—	—	—
Angle of arrival	—	≤70 m	M	M	M	L	C	—	—	—	
Sensor	Dead reckoning	≤10 m	—	M	H	—	M	C or D	—	Y	Y
	Identification of landmarks	≤10 m	—	—	—	—	—	C or D	—	—	—

TABLE 7: Comparison of positioning techniques with algorithms and technologies.

Techniques	Filtering algorithms	Technologies							Limitations
		Cellular	Bluetooth	Infrared	RFID	Wi-Fi	GPS	UWB	
Proximity	Cell ID	Y	Y	—	Y	Y	—	—	Accuracy is not enough for LBS services
	Cell ID with sectors	Y	—	—	Y	—	—	—	Bidirectional antennas are required, which is an extra cost
	Cell ID with TA or RSS	Y	—	—	Y	—	—	—	Proper knowledge of time sync is required, else the estimated position might have a huge impact
	Cell ID with sectors or TA or RSS	Y	—	—	Y	—	—	Y	Same as its predecessors
RSS	Trilateration	Y	Y	—	—	Y	Y	—	Requires a line of sight between transmitter and receiver
	Fingerprinting	—	Y	—	—	Y	—	Y	Building offline database is time-consuming and easily affected by varying environmental characteristics
Time	TOA	Y	—	—	—	—	Y	—	Complex to implement and requires time sync
	RTT	Y	—	—	—	—	Y	Y	Further load is generated on the network traffic to calculate the RTT
	TDOA	Y	—	—	—	—	Y	—	Affected by multipath of signal
Angle of arrival	Triangulation	Y	—	—	—	—	Y	—	Requires additional antennas to measure AoA which is an extra cost
Sensor	Dead reckoning	—	—	—	—	—	—	—	Performance degrades over time due to accumulated
	Identification of landmarks	—	—	—	—	Y	—	—	measurement of noise of sensors

estimated using the broadcasted signals of the access points (AP). Trilateration is a geometry technique that determines the absolute or relative location of an object by measurement of distances using properties of circles, spheres, or triangles [34]. Fingerprinting is a signature-based localisation technique that captures a radio map of values that are matched against a set of prestored signatures to identify an object location [28]. In a different context, the signatures can be geotagged (visual) images, signal, motion, or sound. The most common technologies that inherit fingerprint approach are Wi-Fi, Bluetooth, camera, and microphone.

Angle of arrival (AoA) is defined as the angle between the propagation direction of an incident wave and some reference direction, which is known as orientation [41]. AoA-based positioning techniques rely on the measurement of angles of the node seen by the reference nodes [42]. Triangulation is a common technique in network-based methods, and it locates the mobile devices using the AoA of

received signals of the same by two or more BSs, assuming the distances between the BSs are known [41, 42].

Time-based localisation techniques record a signal's propagation time, also called as time of flight (TOF) to estimate the location of a mobile device. The TOF is converted into its travelling distance from the BS to mobile device, assuming that the signal's propagation speed is already known. Time of arrival (TOA), time difference of arrival (TDOA), and round-trip time (RTT) are common techniques. In many cases, different signals such as radio frequency (RF), infrared, acoustic, and ultrasound are used depending on the localisation requirements [31, 43, 44].

Sensor-based methods use on-board smartphones' inertial sensors to determine the location of users. Gyroscope, accelerometer, and magnetometer are among the common sensors used to calculate users' position. The angular velocity is derived from gyroscope, acceleration from accelerometer, and magnetic fields from magnetometer. The techniques that

are famously categorised under sensor-based are dead reckoning and identification of landmarks [44]. Dead reckoning (DR) techniques estimate the location of a target object based on the last known location, assuming the direction of motion and either the velocity of the target or the travelled distance are known. The classification of landmarks is done in order of their specific sensor patterns that have been tagged at that particular spot. The landmarks can be places like stairs, elevators, escalators, or doors.

*5.1. Discussion of Positioning Techniques with Key Defined Parameters.* Table 6 provides a comprehensive analysis of the base positioning techniques with the key defined parameters. The positioning techniques are evaluated against the derived parameters to identify their strengths and shortcomings. Most of the location-based services require accurate and precise information in real time so that the experience is more real and engaging. Moreover, the systems should take into consideration the limited resources in mobile devices and devise new methods to maintain a consistent performance. Most of the techniques discussed in Section 5 have already been implemented and tested for location-based services.

Proximity techniques have been primarily implemented using cellular network. These techniques are scalable and very simple to implement because they do not require complex algorithms or high computational power. Cell ID identifies the approximate position of a mobile handset by predetermining the BS it is connected. The coverage area is defined with respect to the cell radius, and the location of the mobile phone is estimated within that radius, therefore providing an estimated accuracy of radius  $r$ . Cell ID with sectors techniques employ directional antennas, and thus, the cell is divided into sectors. The accuracy can be inferred as “sector size” using this technique. Time or RSS techniques are taken into consideration for cell ID with time advance (TA) or RSS to estimate the position. In this particular technique, the length of the time of the signal is calculated to reach the BS from the mobile phones. The accuracy can be a denominator of four of the accuracy of cell ID technique [27, 31, 40]. Cell ID with sectors + TA or RSS techniques include clustering of the cell into sectors and employ TA or RSS values to estimate the location of the mobile device, therefore providing a more accurate result than its predecessors. The accuracy of such techniques can be estimated up to denominator of four of the actual sector size.

The RSS category comprises of two techniques, namely, trilateration and fingerprinting. Recently, a number of research studies have been carried out on RSS-based techniques for indoor positioning systems using mobile devices. The widespread diffusion of Wi-Fi hotspots or BLE transmitters in buildings has allowed the implementation of many indoor localisation-aware services. Trilateration is derived from the geometry technique that determines the absolute or relative location of an object by measurement of distances using properties of circles, spheres, or triangles. Such a technique is a good option for the free-space model since it does not suffer from multipath and shadowing issues [33]. Multipath is the propagation of signals in two or more

directions while reaching the transmitter [27]. Shadowing is the effect of received signal power fluctuations due to obstruction between the transmitter and receiver [27]. In this perspective, it follows the power-loss algorithm, where the received power is indirectly proportional to the square of the distance from the source of the transmitter [34]. Fingerprinting techniques have demonstrated good accuracy and precision using Wi-Fi RSS signals. However, it also presents a significant drawback in scalability and flexibility. This technique matches the live signal values with the prestored values in the offline database and provides the positioning information. Yet, a single change in the environment can give false-positive information, thus impacting the flexibility in different context environments [25]. Moreover, a new offline database should be constructed if the system is extended to a new environment, therefore impacting on the scalability [25]. Lastly, RSS-based techniques do not take orientation into consideration. Thus, real-time positioning applications such as augmented reality systems would be very challenging to build using the techniques.

The time-based methods comprise of three techniques, namely, TOA, TDOA, and RTT. TOA can be estimated by measuring the arrival time of a wideband narrow pulse, also known as signal. The distance between the receiving device and the transmitting node can be calculated by the given formula: distance = time  $\times$  speed, where  $D$  is the distance in meters, time is the transmission time delay, and speed is the travelling speed of the signal [43, 44]. This method is highly precise because it can sync with other BSs to locate the object in subject. RTT can be computed by the following formula:

$$D = \frac{(t_{DT} - \Delta t) \times \text{speed}}{2}, \quad (1)$$

where  $D$  is the distance between the transmitting node and the receiving node,  $t_{DT}$  is the total time required for a signal to move from one point to the other and back again,  $\Delta t$  is the time delay needed by the hardware device to operate at the receiving end, and speed is the speed of the transmitting signal [43, 44]. TDOA techniques measure the differences of arrival signal time from different BSs to determine the location of a mobile device. The application of TDOA is used in situation when there is no need for synchronisation between a given node and reference node, but there is synchronisation between reference nodes. It can be expressed using the following formula:

$$\Delta d = c * (\Delta t), \quad (2)$$

where  $c$  is the speed of light and  $\Delta d$  is the difference in arrival times at each reference point [43]. Time-based techniques have presented an improvised method for localisation services, and the accuracy and precision in unobstructed environments are good enough to implement in large scale. The major drawbacks of these techniques are that it offloads additional load on the beacon to calculate the time, and signal multipath can lead to errors in time calculation.

AoA techniques have been scarcely used for localisation of smartphones, and it requires specialised antennas to capture the incident angles bounding on the beacons. The most common method in AoA is triangulation; it locates the mobile devices using AoA of received signals of the same by two or more BSs, assuming the distance between the BSs is known [41, 42]. In a two-dimensional space, the following equation can be used to calculate the location of the device:

$$(x_i - x_{sp})\sin(\theta_i) = (y_i - y_{sp})\cos(\theta_i), \quad (3)$$

where  $x_i$  and  $y_i$  are XY coordinate values of BS,  $\theta_i$  is the AoAs for the received BS signals, and  $x_{sp}$  and  $y_{sp}$  are the XY coordinate values of the mobile device location [41, 42]. In previous related works [21, 22], the accuracy and precision of such techniques are not reliable since it does not function well in varying environmental context.

Sensory-based techniques have been commonly employed in recent positioning-based systems. The availability of sensors in smartphones has allowed an easy adaption and integration of such techniques in the recent positioning-based systems. The two most common techniques in this category are DR and identification of landmarks. DR techniques estimate the location of a target object based on the last known location, assuming the direction of motion and either the velocity of the target or the travelled distance are known. The sensory devices (accelerometer, magnetometer, and gyroscope) work in collaboration to find the resultant positioning information. This technique suffers from noise effects from sensors and could lead to inaccuracies in providing the positioning information [31]. The classifications of landmarks are done in order of their specific patterns that have been tagged at those particular spots. Landmarks can be places like stairs, elevators, escalators, or doors. In addition, it also detects turns in user movement by the variation of the multitude of sensory devices such as accelerometer, magnetometer, barometer, gyroscope, and Wi-Fi. The sensory-based techniques are best suited for indoor environments as they rely mostly on the inertial sensors in smartphones. Inertial sensors consume energies, and this can have a negative impact on the user experience. In addition, developers are usually faced with the challenge to cancel the noise from the sensors to provide a reliable positioning output.

*5.2. Discussion of Positioning Techniques with Algorithms and Techniques.* Table 7 provides a detailed synthesis of the base positioning techniques with the associated filtering algorithms and the related technologies. The limitations of the techniques are derived based on the comparisons carried out in Table 6 and the analysis carried out in Table 7. The filtering algorithms can be classified into deterministic and nondeterministic (probabilistic). In deterministic methods, the previous locations are not taken into consideration to calculate the current positioning information. The probabilistic approaches take into account the last information positioning to calculate (predict) the next positioning information of the user.

As discussed in Section 5.1, proximity techniques are simple to develop and can be integrated easily in large

environments. Such techniques have employed either cellular or RFID technologies because they can be adapted on a large scale with minimal deployment cost. Moreover, the algorithms such as least square (LS), Gaussian distribution, and k-nearest neighbour (KNN) are commonly applied as filtration of raw data from the positioning devices. Precision issues may arise with deterministic algorithm such as LS because of synchronisation and obstructed line of sight (LOS) [32]. KNN algorithms provide a better performance over LS in the cell ID techniques by taking into account the previous localisation information and eliminating the false positives [32].

RSS techniques are widely employed in most positioning systems. Trilateration techniques are commonly applied in GPS technologies and have demonstrated a robust positioning scheme in open areas [24]. As mentioned in Section 5.1, the signal strength is inversely proportional to the distance covered, therefore following a path loss algorithm. In a free model space, the following equations can be employed to find the estimated intensity of the signal:

$$I \propto \frac{1}{D^2}, \quad (4)$$

$$I = \frac{f}{D^2}, \quad (5)$$

$I$  is the intensity of the signal,  $f$  is a known constant, and  $D$  is the distance between the receiving node and transmitting node [28, 34]. This technique has been widely implemented in cellular, Bluetooth, RFID, and Wi-Fi technologies. Fingerprinting techniques have been popular in indoor localisation systems because of its complexity and scalability issues in large environments. Recent works [9, 10, 14] in this area have improved the performance by leveraging on nondeterministic algorithms such as KNN, neural, and SVM. These algorithms have helped in reducing the number of sets of the fingerprint database, but the process is still extensive and exhaustive to build up.

Deterministic algorithms such as LS, two-step iterative, and SLAM are commonly employed in time-based techniques. Wi-Fi and cellular networks are broadly used in such techniques. As discussed in Section 5.1, these techniques are accurate in an unobstructed environment. Yet, synchronisation errors might have adverse effects on the precisions of such techniques. TOA and RTT filter the results using deterministic algorithms. Thus, no prior information is taken into account to estimate the current localisation.

AoA techniques are known to be more complex to implement compared to other positioning techniques since it requires specialised devices to function. Yet, the performance is also dependent on the environment it is deployed. Cellular and Wi-Fi networks are the few technologies that can support AoA techniques. Such techniques use geometric circle intersection and iterative algorithms to filter the data. The geometric circle intersection is derived from the trigonometric concepts, which use a set of circles and parameters (radius and angles) to compute the location of the user [42]. A single error in measuring the incident

angles can have a negative impact on the localisation output.

Sensor-based techniques are commonly applied using the data from the sensors in mobile devices. DR uses Kalman step event algorithm to find the relative position of the device. The accelerometer sensor is employed to detect step events to estimate the position [45]. The data from the sensors indicate a three-axis acceleration relative to the mobile device. The identification of landmarks use similar principles, but it takes into account the uneven variation of the sensors' data to detect the objects. Kalman filter algorithm is employed to filter out the results and to mitigate the noise from sensors [46].

## 6. Review of Positioning Systems

Hybrid techniques are combination of positioning techniques that can provide a more reliable and robust localisation solution for mobile systems. With the advent of high-tech mobile devices, the demands for more accurate positioning systems are continuously rising. It is clear that only one positioning technique cannot address all the current challenges. As such, several systems are integrating a combination of positioning techniques that can work jointly or independently to achieve a more powerful positioning system. In this section, a brief overview and an analysis of the recent positioning systems as listed in Section 2 are carried out. Additionally, the systems are evaluated against the set of defined performance metrics.

Kumar et al. [6] presented a single access point-based indoor localisation for augmented reality gaming for children. The authors have fused the pedestrian dead reckoning (PDR) and fingerprinting techniques to mount the system. Wi-Fi network infrastructure is exploited in this work. An offline database is constructed with the propagation of Wi-Fi signals, and the active system then applies a pattern-matching mechanism with the offline data and the live data to determine the probable locations. The set of results is then transferred to another subsystem to filter out the best-fit position and the orientation of the user based on the input of mobile sensors' data. Accuracy, precision, and orientations are the primary requirements for augmented reality domains. The superimposed images should be laid out at the focal point of the object, therefore allowing the users to visualise complex environments easily. Security and privacy aspects should also be taken into account. Nonetheless, the system should also cater to the security and privacy issues that it can have. Hazard places should be warned to users in advance, and a proper mechanism should be set up to protect the users' personal information (positioning information) as data are shared between users. Table 8 summarises the evaluation of the system. This system can degrade the user experiences because of its low accuracy and precision. However, a good setoff should be formulated between the primary and secondary requirements to enable the system to work flawlessly.

Liu et al. [7] developed a system on indoor localisation based on Wi-Fi (infrastructure) fingerprinting and embedded inertial sensors. The authors introduced a step

detection algorithm with a particle filter mechanism to enhance the conventional fingerprinting technique. The step detection algorithm takes the accelerometer readings to estimate the user's trajectory position. Particle filter is another subset of the system that filters out the least probable user location based on the user's motion and trajectory. These additions have also reduced the bulky preparation required for the Wi-Fi radio maps. This work has demonstrated a robust localisation scheme for indoor localisation using fingerprinting technique. Step detection and particle filter algorithms have eventually enhanced the localisation process to some extent. Though fingerprinting technique can be accurate and precise, it comes with an extensive labour cost. Moreover, this technique can provide erroneous result if the data are not sampled for different devices, i.e., heterogeneity issue. Such a technique can be liable to flooding attacks, whereby an attacker can send several requests to the Wi-Fi router at short lapse of time, thus causing the whole network infrastructure to fail. The evaluation of the system is highlighted in Table 8.

HiMLoc [8] is a solution based on hybrid localisation mechanism that utilised Wi-Fi fingerprinting with PDR technique. The work is similar to Liu et al. [7], but the authors have supplemented their work with an additional component called activity classification. It determines what activity the user is performing within a short interval of time by sampling the data from accelerometer sensor. Besides, it also detects vertical and horizontal movements, for example, if a user is using the staircases or elevator. The authors have considerably reduced the number of Wi-Fi scans, therefore gaining additional battery power to use. The authors have exploited the sensory devices on smartphones to improve the accuracy and precision of the system. Nevertheless, this can also drain the battery very quickly, thus cutting off the user experiences. The accumulation of noise sensors can degrade the accuracy and precision of such system and can provide a wrong localisation estimation. Therefore, users might be concerned about their privacy in case the localisation is not computed correctly. Table 8 highlights the assessment of the work with the defined parameters. A proper trade-off should be devised to lengthen the user experiences without limiting them to a consequent deficiency in the system.

Mashuk et al. [9] implemented a smartphone-based multifloor indoor positioning system for occupancy detection. The proposed positioning framework is developed by creating radio maps using Wi-Fi and Bluetooth (BLE) signals. The authors have introduced map-matching, stair detection, and particle filter mechanism on their model. Besides, accelerometer and gyroscope sensors have been fused to augment the outdated fingerprinting positioning technique. The integration of the commonly available mobile sensors has given an edge to the nondependency to infrastructure positioning systems. The authors have maximised on the multitude of sensory capabilities of smartphones to build up the system. Yet, the system has only achieved a median accuracy of 3.8 m in an indoor environment. Unlike other systems, crowdsourcing data have not been used to create the offline fingerprint database. The

TABLE 8: Evaluation of systems.

Systems	Parameters									
	Accuracy	Precision	Load	Scalability	Flexibility	CD Processing	Heterogeneity	Orientation	Trajectory	
Kumar et al. [6]	<3.5 m	L	M	N	—	C	—	Y	—	
Liu et al. [7]	—	M	H	N	—	C	—	Y	Y	
HimLoc [8]	3 m	M	H	N	—	C	—	Y	—	
Mashuk et al. [9]	3 m–7 m	L	H	N	—	C	—	Y	—	
Gomes et al. [10]	—	H	H	Y	Y	C	—	—	—	
REFIRE [11]	—	L	H	Y	—	C	Y	—	—	
Nazemzadeh et al. [12]	1 m–4 m	M	M	—	—	C	Y	Y	Y	
Wang et al. [13]	—	L	M	Y	Y	C	Y	—	—	
Zhou et al. [14]	<1 m	H	M	Y	Y	C	Y	—	—	
Kok et al. [15]	<1 m	H	L	Y	Y	C	Y	Y	—	
Marton et al. [16]	—	H	M	Y	Y	C	—	—	—	
Anisetti et al. [35]	—	H	M	L	L	C	M	—	—	
Khalifa et al. [17]	—	M	L	—	Y	C	Y	—	—	
Qian et al. [18]	<1 m	M	L	—	Y	C	Y	Y	—	
Kolakowski [19]	<1 m	M	L	—	Y	C	Y	Y	—	
Elbakly and Youssef [36]	L	L	L	Y	Y	C	Y	—	—	
Satan and Toth [20]	—	L	L	—	—	C	Y	—	—	
Prince and Little [37]	<1 m	M	L	L	—	C	—	Y	—	
Tomic et al. [21]	<3 m	M	L	Y	Y	C	Y	—	—	
Tang et al. [22]	—	M	L	Y	Y	C	Y	—	—	
Kumarasiri et al. [23]	<2 m	M	L	Y	Y	D	Y	—	—	

related security and privacy issues are similar to the work of Kumar et al. [6] and Liu et al. [7]. Table 8 highlights an “H” in the load parameter as the mobile sensors are resource-intensive.

Gomes et al. [10] presented an indoor navigation architecture using variable data sources for blind and visually impaired persons. The authors have proposed a hybrid localisation algorithm adaptable to the indoor structures and dealing with different types of signals to increase accuracy. This work is unlike others; it is focussed on a network positioning scheme that involves Wi-Fi infrastructure, BLE, visual tags, or NFC tags. Higher accuracy has been achieved with visual and NFC tags, but it involved huge deployment cost. The authors have focussed their work on the availability of common signals, i.e., Wi-Fi, BLE, NFC, or visual tags. The system has been benchmarked to earn a high precision because of its integration with visual and NFC tags as summarised in Table 8. Fingerprinting techniques are complex to implement under different environments because of the extensive pre-offline database that should be constructed. In this work, the authors have come up to mitigate the fingerprinting issues with other techniques. Moreover, fingerprinting techniques have the common flooding issue that should be addressed.

REFIRE [11] is a framework developed for localising and tracking systems for first responders. The basis of the system has been conceived using the key ideas from robotic localisation. It is built upon the stimulation of proprioceptive sensors such as accelerometer, gyroscope, and magnetometer. In this framework, the authors have modelled trilateration and dead reckoning techniques. Trilateration technique is applied to RFID and cellular network infrastructures, while dead reckoning techniques are applied to the sensors’ data. The accuracy of trilateration on mobile

cellular network can range from sector size to cell size, and it depends on the granularity of trilateration algorithms that the authors have used. In this work, cellular network and RFID tags are used, and the accuracy might be equal to room level. Trilateration techniques can have an adverse effect on the precision of such systems, which eventually have an impact on the operations of the first responders’ team. Besides, noise and drifts from sensors have not been taken into consideration. Thus, this could lead to more inaccurate results. On the other side, this also impacts the precision, which could undermine the user experiences as highlighted in Table 8.

Nazemzadeh et al. [12] developed a position tracking technique based on multisensor data fusion for rollators helping elderly people to move safely in indoor spaces. RFID tags (markers) are allocated to a specific location in the indoor area for detection and tracking of the rollators. The system processes the data from all the sensory devices (encoder, gyroscope, RFID reader, and a Kinect camera). The authors have supplemented their work with a PDR technique with an extended Kalman filter algorithm to filter out the sensor data. In an RFID system, the accuracy is highly dependent on the number of markers and the distances that have been set between them. In other words, it requires a large set of markers to cover for large spaces to achieve a realisable accuracy and precision. The RFID tags can be misplaced by anyone in the indoor environment, thus impacting the functioning of the system and causing a sense of panic among the elderly people. Though the authors have integrated the sensory capabilities in their work, it involves a high cost of deploying RFID tags in the area. Table 8 summarises the evaluation of the system.

Wang et al. [13] presented a work on indoor localisation method by fusing measurement from wearable posture

sensors and the absolute position information from scattered RFID tags. The relative position is calculated from the wearable posture sensors (triaxial accelerometer, gyroscope, and magnetometer). The absolute position is corrected by reading the RFID tags, which are sparsely placed in the indoor environment. The authors have employed a revised Kalman filter algorithm to take care of the sporadic placement of the RFID tags and to cancel out the noises and drifting from sensor data. This work has modelled a prototype indoor localisation mechanism with wearable posture sensors and scattered RFID tags. To some extent, the work can be considered as relatively scalable and flexible because it does not rely on fixed positioned RFID tags. The related privacy and security risks are similar to Wang et al. Table 8 highlights the high scalability and high flexibility of the system.

Zhou et al. [14] presented a joint indoor positioning scheme exploiting PDR and radio frequency tomography. The authors have fused a PDR resetting technique by simple structured geometrical formulation operators. A perfect crossing point can be obtained when users walk across the line-of-sight link of the wireless nodes, which in turn triggers a reset to the PDR mechanism. Besides, the system can also estimate the travelled distance accurately in real time irrespective of the speed at which the objects are moving. The work has demonstrated a robust localisation scheme using PDR technique. As discussed previously, the PDR technique accumulates error with time because of sensor drifts and noise. Hence, this resetting proposed on this work eliminates the risk of having erroneous inputs from multisensory devices. A single change in the environment can impact the whole functioning of the system, thus posing a security threat to the users. However, the work is rated as being highly accurate and takes into consideration the varying characteristics of mobile devices. Table 8 summarises the evaluation of this work.

Kok et al. [15] implemented an indoor positioning approach using inertial sensors and TOA measurements from an ultra-wideband (UWB) systems. A 6D pose is calculated based on the information received from the inertial measurement unit and the TOA from the UWB systems. The work has been extended to cater to the multipath effects and the non-line-of-sight (NLOS) issues caused by the UWB receivers. In the same vein, the system can support multiple IMUs and UWB receivers to achieve a more accurate position and orientation. The authors have devised a novel addition to take care of the multipath and NLOS issues caused by UWB technology. A lot of garbage data is generated in a TOA system. Thus, a proper cleansing is required. Besides, it is imperative to ensure that the clocks synchronisation between the UWB receivers and transmitters is in sync. Interference of signals is another reason that might affect the workability of such systems, arising security and privacy concerns. This system consumes less energy compared to other systems as it relies on simple techniques like TOA, thereof explaining an “L” in the load parameter in Table 8.

Marton et al. [16] developed an indoor localisation system for mobile robots using time-of-flight (ToF)

measurements between an ultrasound signal emitter and ultrasonic sensors. The authors have extended their work on a calibration process to demonstrate the effect of slight anchor (sensors) misplacements. Besides, they formulated a calibration procedure where the necessity of a precise mounting of anchors is not required. Sensor fusion techniques have been used together with the ToF measurements to compute the localisation of the mobile robot. Table 8 summarises the work. This work can be rated as scalable and flexible because of the calibration procedures that the authors have proposed. This procedure can be explored further to validate the performance in a large-scale deployment. However, ultrasonic technologies are costly to implement, and it requires specialised know-how for setup and management. In ToF techniques, the BS is the main actor who controls all the accesses, and it has full control on all the positioning nodes. In the same vein, a single point of failure in the BS infrastructure can compromise all the personal information of the users.

Anisetti et al. [35] developed a robust positioning system that integrates and hybridises information based on RSSI values and database correlation (DCM) technique. The authors presented a localisation system that could improve the accuracy in regions with weak GPS signal and low accurate geolocation. The work is twofold; the authors come with a fingerprinting technique with time-forwarding algorithm and a landmark matching technique using a smartphone camera. The system has been extensively tested in an urban environment. In this study, the work can be classified under the category of fingerprinting and MM technique. The work is conceived to be an alternate solution for geolocation because it is highly accurate and precise. It has the edge over its predecessors because it has the map-matching technique integrates, which makes it highly efficient in filtering all the false-positive locations. However, the scalability and flexibility of such a system will suffer because fingerprinting technique requires an offline database to operate, which makes it challenging to work in a large environment. The evaluation with the key defined parameters is summarised in Table 8.

Khalifa et al. [17] proposed an active pedestrian activity classification for indoor dead reckoning systems. Depending on the target area, activity classification can be complex and challenging to implement on resource-constrained devices. A novel activity classification scheme is proposed in this work to demonstrate its flexibility in complex areas. The system switches the algorithms dynamically based on the context of the environment, demonstrating its flexibility and workability under varying hardware characteristics. Table 8 summarises the review of this system with the defined parameters. The detection of pedestrian activities using PDR and MM techniques can be tricky because of the high risk of errors. As such, the appropriate method is required to leverage the certainties and noncertainties. Moreover, MM techniques usually offload a huge amount of data (images) in the database; thus, these images should be cross verified before uploading as they can contain sensitive information. In this work, the authors have devised a lightweight classification algorithm to preserve more power on devices.

Qian et al. [18] presented an indoor localisation method based on PDR and floor plan information. The work is similar to Khalifa et al. Still, the authors have tackled the drift issues caused by low-cost sensors by applying local gravity crossings value and autocorrelation operations of measured accelerations signal. Moreover, they have also extended the PDR algorithms so that it can take into consideration the limited processing power. The authors have proposed an improved algorithm that could leverage the sensors' noise issues and the limited processing power. In this perspective, it amplifies the user experience and extends the users' activities on the system. The techniques employed in such system provide a better accuracy (1 m), but the precision can be irregular if the MM technique does not find the corresponding information. Table 8 highlights the evaluation of work. PDR with MM is a promising research field, but it also requires a lot of test experiments before it can be scaled up to a large area. The security issues pointed in Khalifa et al. is also applicable in this work.

Kolakowski [19] has developed an improved Bluetooth-(BLE-) based localisation using laser proximity sensors. Trilateration and proximity techniques are combined to form the hybrid localisation techniques of the system. The localisation algorithm consists of two phases; initially, the user position is calculated based on RSS from BLE, and secondly, the laser sensors detect the user's presence in the vicinity. Trilateration is a geometry technique that determines the absolute or relative location of an object by measurement of distances using properties of circles, spheres, or triangles. This technique is most suitable for open areas since it requires a line of sight between transmitter and receiver. Thus, the system might encounter some scalability issues in indoor areas where walls obstruct the signal strength. Table 8 summarises the work with the defined key parameters. In another vein, the misplacement of BLE sensors can influence negatively the functioning of the system, which triggers a possible security and privacy threat to users.

Elbakly and Youssef [36] proposed a cellular network-based outdoor localisation system based on techniques from computational geometry to estimate users' location. The system is extended from the Voronoi diagram of network sites, pairwise comparison between sites, as well as sector information to enhance the localisation accuracy without the need for data collection or special sensors. The system has been tested in urban and rural areas. The authors stressed that it has shown an improvement over the traditional techniques. The Voronoi is derived from triangulation or trilateration techniques. The work from Elbakly and Youssef [36] has focussed on the Voronoi-trilateration technique. This technique is not suitable for an outdoor experiment because it will suffer from accuracy and precision issues. Table 8 highlights the accuracy and precision issues with this system. In another vein, it can be quickly adapted to cellular network because of its low-cost technique. The security and privacy issue associated with cellular network is similar to Marton et al.

Satan and Toth [20] presented an application that is capable of proximity-based indoor localisation using

Bluetooth RSSI. The authors have used a simple algorithm known as path loss model to estimate the distance from the beacons. The user's position is then determined using both the estimated and the closest transmitter to the user. Besides, the system used the nearest neighbour model to find the closest rooms to the user. The authors demonstrated a simple localisation mechanism using BLE technology. BLE has a shorter wavelength compared to Wi-Fi. Thus, it works well mostly in indoor environments. The work has not considered on the impact of slightly changing the position of the beacon. Therefore, it affects both the scalability and flexibility of the system. As data (e.g., RSSI, distance, and location) are stored centrally, a database corruption can arise a possible security threat to the functioning of the system. Table 8 summarises the work with the key defined metrics.

Prince and Little [37] implemented a two-phased hybrid RSS-AoA technique for indoor device localisation using light sensors. The system has the capability of measuring signal strength, azimuth (angles), and elevation in a smart space environment. The mobile nodes estimate their locations through a two-phased approach, the coarse and fine estimations. The "coarse" algorithm measures the signal strength of the Wi-Fi signals and the incident angle of the light with a unique ID to estimate a coarse positioning information. The "fine" algorithm estimates improvement upon the "coarse" by measuring the bearing and elevation angles from the light sensors and applying the geometric triangulation techniques to refine the result. The authors have confirmed a median accuracy of 34.88 cm using the "coarse" algorithm and a median accuracy of 13.95 cm using the "fine" algorithm. The reported accuracies can be accepted in an indoor environment, but the system should ensure that it continues to work well in different lighting conditions. Table 8 evaluates the work with the key defined metrics.

Tomic et al. [21] presented a hybrid RSS-AoA technique for a 3D node localisation in a noncooperative wireless sensor networks (WSNs). Range and angle measurements are extracted from RSS and AoA information. The authors have employed LS to derive a novel objective function from solving the hybrid localisation problem. A second-order cone programming (SOCP) is then applied to obtain a convex function from a nonconvex one. This work has exploited the RSS and AoA techniques using LS and SOCP models. The system has been tested successfully thoroughly in various scenarios including in high-noise situations. The system achieved an accuracy of less than 3 m in an indoor environment, yet it can be slightly improved with additional antennas. However, a slight error in measuring the incident angles can have an adverse effect on the positioning system. Table 8 evaluates the system with the defined parameters.

Tang et al. [22] presented a study on RSS and AoA localisation in life detection in a huge disaster situation. Cellular networks have been used, and techniques such as AoA, proximity, and trilateration have been exploited. The AoA has been calculated from the differences of the RSSI (cellular). The proximity technique includes clustering of the cell into sectors, and it used the RSS values to estimate the location of the mobile device. The system has been conceived

to assist in life detection after huge disaster. With respect to its functionality, the system has been tested mainly in outdoor environmental conditions. A cellular cell size can vary from 2 km to 20 km, and the system has been designed considering this aspect. Therefore, the accuracy and precision achieved are relatively good with regard to the nature of the system. This work has similar related security issue as Tomic et al. [21]. Table 8 assesses the system with the key defined parameters.

Kumarasiri et al. [23] developed a hybrid localisation algorithm for WSN that combines both RSS and time difference of arrival (TDOA). The work also incorporates the RSS information from a widely available Wi-Fi network, which cooperatively functions with the WSN. The proposed technique has been implemented based on two estimators: Taylor series expansion and maximum likelihood. The author has presented a novel hybrid localisation scheme based on a distributed WSNs. The WSNs function independently and do not rely on a centralised node. In this model, the system processing is not impacted in case if one of the nodes fails. As it relies on BS to calculate the time differences, a man in the middle can intercept the signal and send false or erroneous information. Table 8 summarises the system.

## 7. Challenges and Research Directions

In this section, the challenges, trends, and research directions of the mobile-based positioning techniques are discussed. Existing gaps and further improvements on the hybrid positioning techniques are identified and assessed to further enhance the capabilities of mobile positioning-based systems. These are summarised in the following paragraphs.

The combined techniques which involve RSS and fingerprinting are constrained to environmental characteristics. A small object displacement can impact the proper functioning of the systems. Therefore, scalability and flexibility are the principal concerns that should be taken care of while designing positioning systems that use these techniques. In the same vein, the offline database in fingerprinting techniques is very time-consuming and complex to build. New methods should be devised to reduce time and complexity.

Lately, new sensors are incorporated in mobile devices which have not yet been exploited to their maximum capacities. These sensors can be further used to achieve a more accurate and precise positioning which can be extended to several positioning solutions including location-based mobile augmented reality systems. Yet, sensory techniques or a combination of these techniques have a significant drawback. Extensive usage of sensors can lead to noise and drift and accumulates error which could deteriorate the accuracy and precision of such system. In this perspective, additional research should be carried out to leverage the noise and drift errors over a period of time.

Hybrid time-based techniques are commonly used in many positioning systems because of its easy integration in base positioning techniques. The accuracy and precision have considerably been improved over the conventional time-based methods. Time synchronisation is

critical to the proper functioning of such systems; a slight error in time can cause inaccuracies. Asynchronous transmitter is a potential research area that can be exploited to eliminate the time synchronisation issues. In asynchronous transmitter, data flow in a half-duplex mode whereby it uses a parity bit to tell the receiver how to decipher the data.

Hybrid proximity techniques are commonly used for outdoor environments as it is more scalable and flexible to deploy in large scale. In addition, this technique is also known to consume less energy because it uses simple proximity algorithms. However, proximity with the cellular network can lead to accuracy and precision issues since it covers a large area.

Heterogeneity is a critical parameter that should be handled effectively by positioning designers. For example, hybrid Wi-Fi fingerprinting techniques are dependent on the types of Wi-Fi hardware that have recorded the signals to build up the fingerprint databases. Different mobile devices can have different Wi-Fi adapters. Thus, it can lead to heterogeneity issues. In such cases, more research should be carried out to cater the cross-technology and provide an aligned positioning service for all types of devices.

Distributed computing has merely been implemented in existing positioning systems. Among the reviewed works, only one work has proposed this aspect. In a world where cloud computing is dominating, distributed computing can be extrapolated on positioning systems so that positioning can be determined cooperatively instead of a single processing node.

Security and privacy is an important aspect that should be taken into account when designing and developing positioning systems. The objective of this work was focussed on the evaluation of the positioning techniques and systems with the positioning metrics and has not concentrated on evaluating the techniques with security and privacy parameters.

Many surveys in this area have focussed on providing advantages and disadvantages of common localisation techniques, but did not focus on the recent hybrid positioning techniques. Moreover, there is a lack of focus on the challenges that mobile devices can be poised. Presently, mobile devices are contained to have more resources, but they still have limited capacities that could be detrimental to user experiences in mobile position-based systems. In this endeavour, the selection of the positioning techniques and associated algorithms should be made carefully to assess the trade-off between accuracy and complexity.

## 8. Conclusion

In this paper, a survey of the mobile positioning techniques has been presented. Initially, the common positioning techniques have been briefly described, categorised, and assessed to have a comprehensive understanding of the mobile-based positioning methods. As such, mobile positioning techniques are turning towards hybrid ones. A categorisation of hybrid positioning techniques is

demonstrated through the use of a taxonomy and 2D diagram. The recent mobile positioning systems with hybrid techniques from the year 2012 to 2018 have been methodically selected and listed. In turn, the systems have been described, assessed, and evaluated using several key defined parameters. More and more mobile positioning systems are focussing on a more refined positioning algorithm that could be adapted to various contexts. From the evaluation carried out in this paper, it is clear that there is no one technique that is a winner in all situations. Hybrid positioning technique is still an area that can be further investigated and drilled down to new research directions for mobile systems. In most mobile positioning systems, the authors have referenced hybrid techniques as a combination of two techniques. Therefore, this survey is limited to the hybrid positioning techniques with a combination of two techniques. The future work will emphasise on the survey of the mobile positioning system with a combination of three or more methods.

### Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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