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A Survey on Radio Frequency based Precise Localisation Technology for UAV in GPS-denied Environment

Beiya Yang · Erfu Yang*

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Abstract Owing to the specific characteristics of Unmanned Aerial Vehicles (UAVs), the demands and applications increase dramatically for them being deployed in confined or closed space for surveying, inspection or detection to substitute human. However, Global Positioning System (GPS) may lose effectiveness or become unavailable due to the potential signal block or interference in that operational environment. Under such circumstances, an imperative requirement on new positioning technology for UAV has emerged. With the rapid development of Radio Frequency (RF) based localisation technologies, leveraging small wireless sensor nodes for low-cost, low latency, low energy consumption and accurate localisation on UAV has received significant attention. However, no up-to-date review has been conducted in this area so far. Therefore, this paper aims to give a comprehensive survey on the RF based localisation systems with different radio communication technologies and localisation mechanisms on UAV positioning. Toward this end, an exhaustive evaluation framework is first established to evaluate the performance of each system on UAV positioning from different perspectives. Particularly, the Ultra-wideband (UWB) based system with time-based mechanisms is highlighted for UAV positioning under the consideration of the proposed evaluation framework. Finally, an intensive analysis is conducted about the current challenges and the potential research issues in this area in order to identify the promising directions for future research.

Keywords Unmanned Aerial Vehicles (UAVs) · Radio Frequency (RF) · Localisation Technology · Wireless Sensor Node

Beiya Yang
Department of Design, Manufacturing and Engineering Management, University of Strathclyde, Glasgow G1 1XJ, U.K.
Tel.: +44-7529203131
E-mail: beiya.yang@strath.ac.uk

Erfu Yang, corresponding author
Department of Design, Manufacturing and Engineering Management, University of Strathclyde, Glasgow G1 1XJ, U.K.
E-mail: erfu.yang@strath.ac.uk

1 Introduction

With the rapid development of Unmanned Aerial Vehicles (UAVs) technology, their applications are no longer limited to open environments. Exploiting UAVs to substitute human for surveying, inspection, inventory management and emergency rescue in closed, confined, inaccessible or potentially dangerous space has already become a much-sought research direction [1–6]. However, all these applications summarised in Fig. 1, are homogeneously within the environments where Global Positioning System (GPS) is insufficient or unavailable to provide precise position information needed for UAV, due to the satellite signal lost or interference, which is also denoted as the GPS-denied environment. Under such circumstances, the demand for new positioning technology to achieve the precise localisation of UAV in that operational environment becomes impressively.

Before the detailed overview on the localisation technologies for UAV positioning, all the acronyms utilised in the following content are summarised in Table 1, to be a guidance and reminder for reader to understand each of them.

Currently, different localisation technologies have been developed for UAV positioning, such as Vision, Inertial Navigation System (INS), Infrared, Lidar, Ultrasonic and Radio Frequency (RF) based localisation technologies, where Table 2 provides a comparison for all these technologies. Among these, vision-based localisation technologies consisting of Visual Odometry (VO) and Motion Capture Systems (Vicon, OptiTrack) are known as ones with the highest accuracy which often serve as the ground-truth for performance evaluation. At present, the vision-based approaches especially for VO are the most widely utilised technologies on UAV positioning. Due to the highest accuracy and low prior information requirement, the UAV positioning with vision-based technologies is suitable for the rescue or exploration missions in unknown environment. Moreover, with the captured image information, the collision avoidance, mapping and smart path planning are able to be implemented which is critical for UAV navigation. However, the low-visibility condition and error accumulation for VO, tedious procedure for the deployment and extremely expensive system cost of Motion Capture Systems will all restrict their applications on UAV. On the other hand, the INS is the other widely used localisation technology for UAV due to the existing of built-in Inertial Measurement Unit (IMU) in flight controller. Yet, the error accumulation and external magnetic field effects will lead to the accuracy degradation. Thus, the INS based approaches are often served as part of the sensor fusion method for UAV positioning to smoothen the localisation result. Apart from vision-based technologies and INS, there are still some other localisation technologies being applied on UAV in recent years. For instance, the Ultrasonic localisation system developed by Marvelmind has been applied and tested by lots of researchers [7–10]. It is able to provide up to 2cm accuracy for UAV positioning. With the on-board battery, the Ultrasonic sensor nodes also have no influence on the UAV operation time. Nevertheless, considering the inherent nature of acoustic waves, system performance will drop sharply in cluttered environment, the localisation coverage is limited and the auxiliary nodes are required for localisation [11]. Furthermore, the Infrared and Lidar based localisation technologies are also able to provide the centimetre-level accuracy in GPS-denied environment which have already attracted lots of attention on UAV positioning. Apart from the positioning, the precise feature map of the environment can also be established by the Infrared and Lidar based technolo-

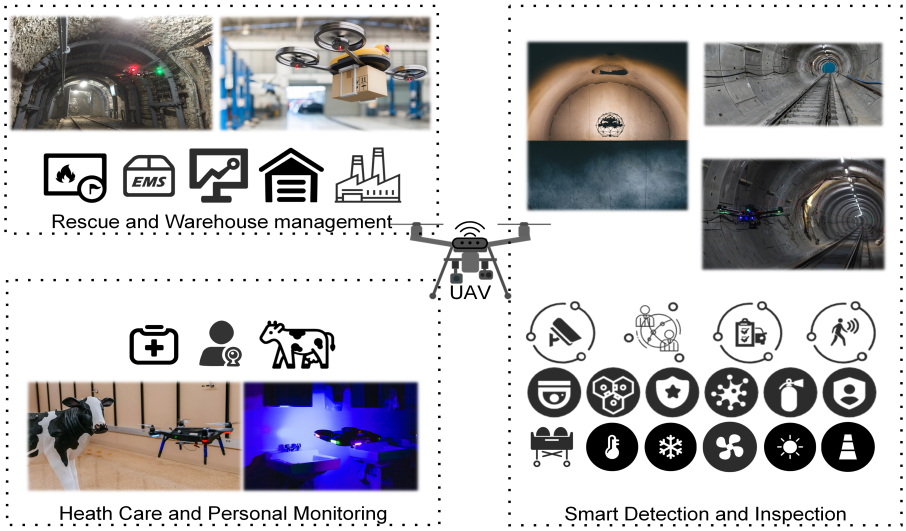

Fig. 1 UAV applications in GPS-denied environments

gies with no extra equipment required, which is significant for the UAV navigation in unknown and GPS-denied environment. However, these technologies will all be susceptible to the unpredictable signal occlusion [12]. The communication range for the infrared systems are limited within 2m to preserve the accuracy. System cost and extremely high energy consumption will also restrict the application scenarios of the Lidar based systems on UAV positioning.

Owing to the rapid development and existing characteristics of the RF based localisation systems such as low-cost, low latency, low energy consumption and centimetre-level accuracy, their applications for UAV positioning have emerged in recent years. From the system structure shown in Fig. 2, the UAV position information can be directly extrapolated through the communication between the anchor nodes (auxiliary nodes with known position help for positioning) and tag node (the sensor node needs to be positioned). All the sensor nodes are able to power themselves with the on-board battery which has no impact on UAV operation time. Moreover, unlike the vision-based technologies, the RF based localisation technologies will never suffer from the low-visibility condition and error accumulation. Nevertheless, in contrast to other localisation technologies, the RF based localisation approaches still have their limitations. Firstly, the additional anchor nodes with the prior location information are required. Secondly, the localisation performance is limited by the communication condition between the anchor nodes and tag nodes. Thirdly, the RF based localisation systems cannot provide the orientation information for UAV positioning. To solve the existing limitations and improve the localisation accuracy, the sensor fusion methods which combined the RF with other technologies are also proposed in recent years. With the additional approaches, it becomes possible to provide the orientation information, the requirement of the prior information can be reduced and the performance fluctuation caused by the measurement noise can be filtered out, which is particularly important for the stable control of UAV in GPS-denied environment.

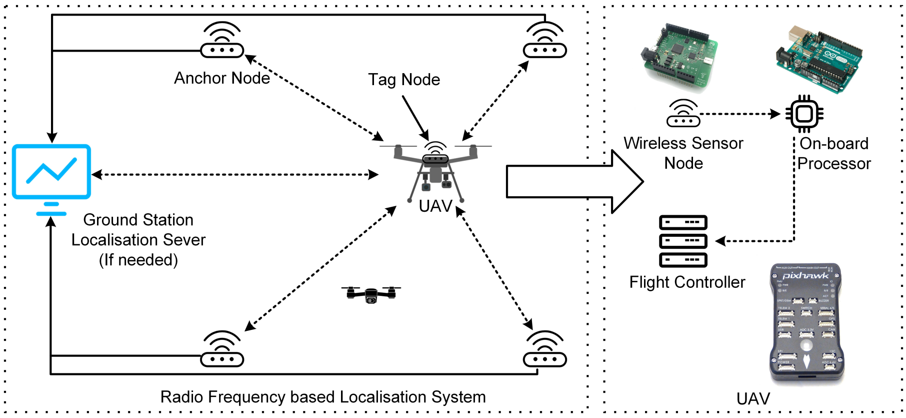

Fig. 2 Localisation structure for RF based UAV localisation system

Nevertheless, the system performance may be restricted by the limitation of one localisation technology. For instance, the fusion method based on RF and Vision may lose the effectiveness in the low visibility condition and the performance of the fusion method based on RF and INS may be influenced by the external magnetic field effects. Moreover, the additional components may lead to the increase of the system cost and energy consumption which also need to be considered. Despite defects exist, the RF based localisation technologies still attract lots of attention on UAV positioning in GPS-denied environment due to the existing characteristics. As shown in Fig. 3, a fast growth can be seen in the past few years.

However, no up-to-date review has been conducted in this area currently. Some existing survey in [13, 14] mainly focused on the overview for all the existing indoor localisation or ranging technologies, no specific technology or application is considered. Some of the review articles in [15, 16] paid a close attention to the RF based indoor localisation technologies, but still no specific application was considered. Others in [17–19] mainly focused on the overview of the existing UAV localisation and navigation technologies in GPS-denied environment, the detailed review for the RF based technologies was not presented. Most recently, Shule et al. [20] reviewed the localisation technology for multi-UAVs and multi-robot leveraging Ultra-wideband (UWB) based system is the most relevant paper in this area. However, the comparison and discussion for other radio communication technologies and localisation mechanisms on UAV positioning were not considered. According to our investigation, a review focusing also on the RF based localisation technologies and UAV positioning is currently missing from the literature, despite its necessity. Therefore, it is crucial to provide a comprehensive overview and detailed discussion on the RF based UAV localisation technologies in GPS-denied environment to identify the promising directions for further research. To further present the difference and verify the significance of our work, the comparison with the existing survey in the relevant area is given in Table 3.

The main contributions for this paper are listed as follows:

– A comprehensive overview for the existing RF based UAV localisation systems with different radio communication technologies is provided. The pros and cons

Table 1 List of Acronyms

Acronyms	Full Name	Acronyms	Full Name
6-DOF	6 Degrees of Freedom	AWGN	Additional White Gaussian Noise
AOA	Angle of Arrival	AOD	Angle of Departure
AI	Artificial Intelligence	ATPL	Asymmetrical Time-stamping and Passive Listening
AER	Auxiliary Equipment Requirements	BLE	Bluetooth Low Energy
CIR	Channel Impulse Response	CSI	Channel State Information
CNN	Convolutional Neural Network	CI	Covariance Intersection
DOA	Direction of Arrival	DS-TWR	Double-sided Two-way Ranging
EC	Energy Consumption	EKF	Extended Kalman Filter
FIR	Finite Impulse Response	FTSP	Flooding Time Synchronisation Protocol
GNSS	Global Navigation Satellite System	GPS	Global Positioning System
HAIP	High Accuracy Indoor Positioning	HiQuadLoc	High-speed Quadrotor Localisation
IVM	Import Vector Machine	IMU	Inertial Measurement Unit
INS	Inertial Navigation System	inverse-NDFT	inverse Non-uniform Discrete Fourier Transform
KF	Kalman Filter	KFPF	Kalman Filter and Particle Filter
KPIs	Key Performance Indicators	LS-SVM	Least Square Support Vector Machine
LC	Linear Consensus	LOS	Line-of-sight
LA	Localisation Accuracy	LCR	Localisation Coverage
L/U	Localisation Latency/ Update Rate	LR-WPAN	Low-rate Wireless Personal Area Networks
MAVs	Micro Air Vehicles	MDS	Multidimensional Scaling
NLR	Non-linear Regression	NLOS	Non-line-of-sight
OFDM	Orthogonal Frequency Division Multiplex	RF	Radio Frequency
RFID	Radio Frequency Identification	RTLS	Real Time Location Service
RSS	Received Signal Strength	RNN	Recurrent Neural Network
RBS	Reference-broadcast Synchronisation	RVM	Relevance Vector Machine
RVs	Relevance Vectors	RMSE	Root Mean Squared Error
SOCR	Second-order Cone Relaxation	SDR	Semidefinite Relaxation
SALMA	Single-anchor Localisation System using Multipath Assistance	SPEAR	Source Position Estimation for Anchor position uncertainty Reduction
SIG	Special Interest Group	SDE	Stability in Different Environment
SVM	Support Vector Machine	SVs	Support Vectors
SDS-TWR	Symmetric Double-sided Two-way Ranging	SC	System Cost
TDOA	Time Difference of Arrival	TOD	Time of Departure
TOF/TOA	Time of Flight/Time of Arrival	TPSN	Timing-sync Protocol for Sensor Networks
TWR	Two-way Ranging	TW-TOF	Two-way Time of Flight
UHF	Ultra-high Frequency	UWB	Ultra-wideband
UAVs	Unmanned Aerial Vehicles	UKF	Unscented Kalman Filter
VO	Visual Odometry	W/S	Weight/Size
WCL	Weighted Centroid Localisation	WLPS	Wireless Local Positioning System

Table 2 Comparison for conventional technologies on UAV positioning

	Accuracy	Localisation Coverage	System Cost	Deployment Difficulty	Weaknesses
Vision Odometry	Up to centimetre	N/A	Low	Low	Suffer from low-visibility condition, error accumulation
Motion Capture System	Millimetre accuracy	Around 6-30m for each camera to preserve the accuracy	Extremely high	High	Extremely high system cost, hard to deploy
INS (IMU)	Up to decimetre	N/A	Low	Low	Error accumulation, external magnetic field effects
Ultrasonic	Up to centimetre	Up to 10m	Low	Medium	Vulnerable to Non-line-of-sight (NLOS) path and environment variables, require auxiliary nodes, no orientation information
Infrared	Up to millimetre	Up to 2m	High	Medium	Small coverage, vulnerable to NLOS path, high system cost, no orientation information
Lidar	Up to millimetre	N/A	High	Low	High system cost, vulnerable to NLOS path, high energy consumption
RF	Up to centimetre	Up to 300m	Low	Medium	Require auxiliary nodes, high communication cost, vulnerable to NLOS path, no orientation information
Sensor fusion based on RF and other technologies	Up to centimetre	Up to 300m	Medium	Medium	System performance may be restricted by the limitation of one localisation technology, the additional components may lead to the increase of the system cost and energy consumption

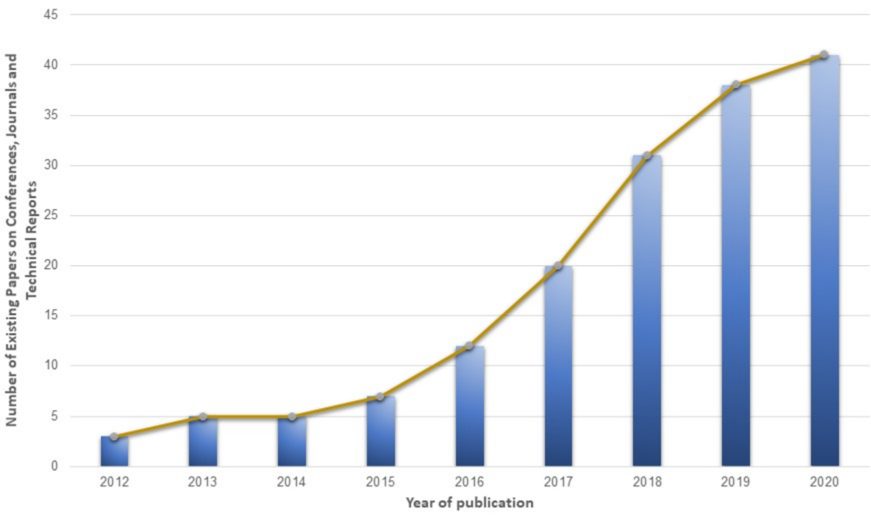

Fig. 3 Publication (Google Scholar) on RF based UAV localisation technologies up to the given year

Table 3 Comparison with the existing literature

Existing Literature	GPS-denied Localisation or Ranging	Localisation Mechanism	RF Localisation	UAV Positioning	Evaluation Framework for UAV Application	Existing Challenges
Brena et al. [13]	Yes	Yes	Yes	No	No	Yes
Singh et al. [14]	Yes	No	No	Yes	Yes	Yes
Zafari et al. [15]	Yes	Yes	Yes	No	No	Yes
Yassin et al. [16]	Yes	Yes	Yes	No	No	Yes
Pérez et al. [17]	Yes	No	Yes	Yes	No	Yes
Lu et al. [18]	Yes	No	No	Yes	No	Yes
Balamurugan et al. [19]	Yes	No	No	Yes	No	No
Wang et al. [20]	Yes	No	Yes	Yes	No	No
Our work	Yes	Yes	Yes	Yes	Yes	Yes

of each system is discussed to highlight their suitability and challenges on UAV positioning.

- A detailed survey and discussion for the classical localisation mechanisms with the existing RF based UAV localisation systems are given to analyse their possibility and suitability on precise UAV positioning in GPS-denied environment.

- Considering the lack of assessment system, an evaluation framework is established to provide an overall consideration and rational estimation on Key Performance Indicators (KPIs) of UAV positioning with RF based localisation technologies in GPS-denied environment. The current RF based UAV localisation systems are assessed under the proposed framework to provide the evidence for challenge discussion.
- Finally, in order to provide a clear guidance for future research, an in-depth discussion and generalisation are given for the current challenges and potential research issues on UAV localisation with RF based technologies in GPS-denied environment.

The rest of paper is structured as follows. Section 2 elaborates the existing RF based UAV localisation systems with different radio communication technologies, gives a comprehensive overview and discussion of each to analyse the pros and cons. Subsequently, a review and comparison for the classical localisation mechanisms with RF based UAV localisation systems such as Received Signal Strength (RSS), Angle of Arrival (AOA), Time of Flight/Time of Arrival (TOF/TOA), Time Difference of Arrival (TDOA) and Fingerprint etc. are presented in Section 3 to evaluate the effectiveness on UAV positioning in GPS-denied environment. Section 4 mainly focuses on the establishment of evaluation framework to comprehensively assess the current RF based UAV localisation systems. Section 5 analyses the current challenges for RF based localisation technologies on UAV positioning, gives the discussion on the pros and cons for current solutions and potential research issues in this area to serve as the guidance for future research. Finally, a conclusion is given in Section 6 to summarise the full paper.

2 RF based UAV Localisation Systems

In this section, an overview of the existing RF based UAV localisation systems with different radio communication technologies are elaborated. Subsequently, an in-depth discussion and analysis for the suitability and challenges of each technology on precise UAV localisation are presented. Moreover, several state-of-the-art RF based localisation systems which successfully achieve decimetre-level localisation accuracy are also reviewed, owing to the potential applications on UAV localisation in the future. Radio communication technologies including Wi-Fi, Bluetooth, Zigbee, Radio Frequency Identification (RFID) and UWB based localisation systems shown in Fig. 4 are discussed in detail in the following subsections.

2.1 Wi-Fi based Localisation System

Wi-Fi, belonging to the IEEE 802.11 standard family, is known as one of the most commonly used wireless network technologies in the last several decades. Due to the universality, Wi-Fi turns into one of the simplest implementation localisation technologies, and several researches have already been done on UAV positioning.

In [21], a Wi-Fi based precise UAV position estimation and collision avoidance system was implemented through the consideration of coloured measurement noise model and localisation with Extended Kalman Filter (EKF). Differently, another

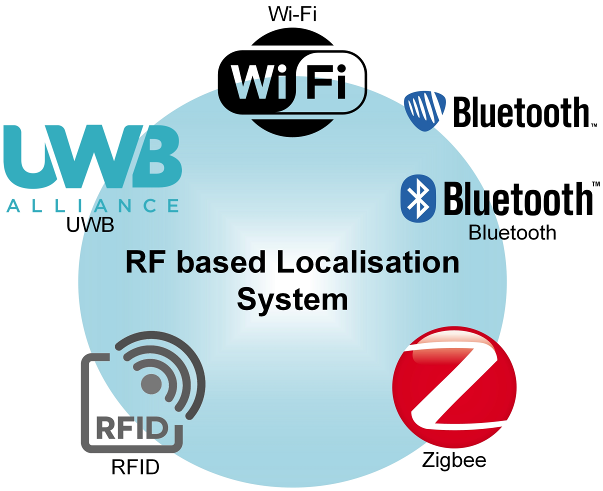

Fig. 4 RF based localisation systems

Wi-Fi based UAV navigation system was designed in [22], with linear Kalman Filter (KF) to lower the computational complexity of EKF for energy consumption reduction. On the other hand, different from the localisation with single technology, a cooperative UAV localisation approach was proposed in [23]. With the combination between Global Navigation Satellite System (GNSS), UWB, IMU and Wi-Fi, a decimetre-level localisation accuracy was achieved. However, the accuracy was reduced to 3m when only Wi-Fi module exists. Considering the meter-level accuracy, only outdoor application is suitable for the aforementioned systems. To further improve the accuracy, the algorithm proposed in [24] leveraged Multidimensional Scaling (MDS) and Weighted Centroid Localisation (WCL) achieved decimetre-level localisation accuracy. However, many more access points (anchor nodes) are required to preserve the accuracy and the evaluation has only been done in simulation. Importantly, the influence of NLOS error caused by unpredictable people or object was not taken into account for all the aforementioned systems.

As discussed, UAV positioning with Wi-Fi based localisation system is still restricted owing to the unacceptable accuracy and unreliable performance. However, the development of Wi-Fi technology and introduction of additional equipment like massive antenna array still preserve the opportunity for decimetre-level accuracy and reliable localisation performance with Wi-Fi based system. Currently, the most popular works in this area are Chronos [25] and SpotFi [26]. They all achieved decimetre-level accuracy with Wi-Fi based system but under different methods. In [25], frequency hopping was exploited for emulation of wideband radio to enhance the bandwidth of Wi-Fi signal. Time resolution is inversely related to the radio bandwidth, that is the reason why precise time-based measurement can be obtained. Meanwhile, Orthogonal Frequency Division Multiplex (OFDM) and inverse Non-uniform Discrete Fourier Transform (inverse-NDFT) were applied to eliminate the packet detection delay and identify direct path to keep system performance in NLOS environment. Finally, a median accuracy of 65cm in Line-of-sight (LOS) and 98cm in NLOS environment were attained with the off-the-shelf commercial Wi-Fi modules. Moreover, system performance was tested on a commercial drone (AscTec Quadrotor) where the Root Mean Squared Error (RMSE) of relative distance was 4.2cm. However, in strong NLOS environments it will lose effectiveness, due to the dominant peak of Channel Impulse Response (CIR) not necessarily characterising the direct path. In addition, energy consumption of the system keeps high owing to the sweep of multi-frequencies. Unlike [25], [26] introduced AOA for precise localisation. A super-resolution algorithm was presented for precise AOA computation and combination of AOA and TOF was utilised for direct path identification to overcome the influence of NLOS path in cluttered environment. Finally, the median error of 0.4m and 1.6m were achieved in LOS and strong NLOS scenarios. However, with additional antenna array, the operation time and application scenarios will be restricted. In order to reduce the communication cost and exclude the additional components, Li et al. [27] designed a TDOA based localisation approach with commercial 80MHz Wi-Fi system achieved 0.23m and 1.5m accuracy for outdoor and indoor applications which is much more suitable for UAV localisation. However, a localisation server and additional synchronisation algorithm are needed for precise localisation. Moreover, many more sniffer nodes (anchor nodes) are required to be deployed to preserve the accuracy in NLOS environment.

On the other hand, lots of fingerprint-based approaches emerge in recent years, which are able to achieve the decimetre-level accuracy with Wi-Fi based system [28–34]. However, with the inherent rule of fingerprint, it is not suitable for UAV localisation in dynamic or unknown environment, detailed information will be given in Section 3.5.

2.2 Bluetooth based Localisation System

Bluetooth, a family member of the IEEE 802.15 standard, also known as one of the extensively utilised communication technologies in our daily life, which works on the same frequency band compared with Wi-Fi. But Bluetooth shows low cost, lower energy consumption and small size features, especially with the emerging technology Bluetooth Low Energy (BLE) developed by Bluetooth Special Interest Group (SIG) [35]. With the aforementioned characteristics, scientific researches and applications on precise localisation technology based on Bluetooth or BLE are growing dramatically in recent years. However, due to the limited bandwidth, low cost and low energy consumption features, it is unrealistic to implement time-based or angle-based localisation mechanisms on Bluetooth based localisation systems. Therefore, RSS turns into the most commonly used localisation mechanism for Bluetooth and BLE.

Currently, several Bluetooth based localisation systems have already been designed for UAV positioning in GPS-denied environment. In [36], a UAV patrol system was designed for UAV navigation in GPS unstable area through RSS measurements from Bluetooth beacon. In both [37] and [38], relative localisation for UAV swarm was achieved with Bluetooth beacons. To improve the accuracy, authors in [37] and [38] all fused the other measurements such as odometry, altitude, velocity and displacement information from additional components with RSS from BLE and Bluetooth beacons achieved precise localisation and collision avoidance of UAV. Apart from the applications on UAV, [39] and [40] both presented the

Bluetooth based localisation system for robot navigation in GPS-denied environment. The authors in [39] mainly focused on RSS calibration, leveraged 10th order Finite Impulse Response (FIR) filter for measurement noise mitigation which finally achieved a nominal error of 10cm on distance measurement. Whereas, the authors in [40] more focused on the distance obtaining and position estimation methods to improve the performance. A novel method for distance estimation and trilateration approach was proposed which achieved final error of $0.427 \pm 0.229m$.

In addition, some commercial BLE based localisation systems which can achieve decimetre-level accuracy are also reviewed in this paper, due to the potential for UAV positioning. iBeacon [41] proposed by Apple Inc in 2013 is the typical representative. In [42], the localisation performance of iBeacon was evaluated with different placement patterns. Where the average accuracy below 1m was obtained, but only in open environment. For accuracy improvement, a joint Kalman Filter and Particle Filter (KFPF) algorithm was presented and implemented with iBeacons in [43] which successfully achieved the median localisation error of 0.7m and 0.947m in 2D and 3D environment and showed robustness in NLOS environment. However, the accuracy was obtained with seven iBeacons, as only three iBeacons exist, accuracy decreased by half. Besides, with the high computational complexity, the localisation latency and system reliability will also be influenced. Therefore, further research is still required for UAV applications. Rule out of iBeacon, other commercial systems which utilise BLE for precise localisation, like High Accuracy Indoor Positioning (HAIP) [44] developed by Nokia and Gimbal proximity beacon [45] presented by Qualcomm all keep the possibility for UAV localisation in GPS-denied environment. However, further research is still required especially for the problem of small localisation coverage and vulnerable to NLOS path.

2.3 Zigbee based Localisation System

Zigbee is the communication protocol that standardises the higher layers of the protocol stack under the IEEE 802.15.4 standard. It defines the characteristics of the physical and MAC layers for Low-rate Wireless Personal Area Networks (LR-WPAN) [46]. Zigbee shows low data rate, low energy consumption and low-cost features which is targeted towards monitoring, automation and remote-control applications [47]. Compared with Bluetooth, Zigbee shows lower data rate, lower energy consumption, longer coverage range and accommodate up to 65000 communication nodes for one sub-network. However, Zigbee still vulnerable to the influence of NLOS path and low data rate may cause high localisation latency which runs counter to the requirements on UAV. Thus, only one scientific paper utilising Zigbee based system for UAV localisation has been carried out currently, according to our investigation. In [48], a UAV localisation system was proposed which combined Zigbee with INS achieved the absolute accuracy of 20cm on an automated quadrotor APM 2.0. However, the influence of NLOS path was not considered, system performance was only tested in open area. Meanwhile, the localisation latency was not mentioned, only a sampling rate for localisation at 1s was set in simulation platform.

2.4 RFID based Localisation System

RFID is designed as a wireless communication mean which utilises RF electromagnetic fields for identification and tracking. On the basis of response mode, RFID tag nodes can be divided into three categories [49]:

- Passive tag. Receive signal passively and answer back using the power from the emitted signal by the RFID reader. There is no requirement of internal power source, smallest size and lowest cost within all the types of RFID tag nodes. However, communication range is limited (roughly one to five meters).
- Semi-passive tag. It receives signal passively, but utilises the on-board battery to generate the transmitting power. Additional function such as real-time tracking or environment detection can be provided. However, communication range still remains short and new problems such as extra weight, larger size, higher cost, shorter life and temperature sensitivity are brought in [50].
- Active tag. It is able to transmit signal actively with the on-board battery. It mainly utilises in Real Time Location Service (RTLS). It has the ability to broadcast signal periodically for data communication and localisation. However, its weight, size, cost and energy consumption also need to be considered.

Meanwhile, the aforementioned nodes are all sensitive to harsh environments and contribute to radio noise which may seriously degenerate localisation performance.

Considering the unique characteristic of passive RFID node, scientific researches on UAV localisation with this technology have emerged in recent years. Within them, two different systems designed by Zhang et al. in [51] and [52] are the typical representative. In [51], a RFID based 6 Degrees of Freedom (6-DOF) enhanced localisation system for UAV called RFUAV was designed. Thanks to the small size and no power supply feature of passive RFID, position and orientation information could be garnered through communication between RFID readers and the passive RFID tag nodes ($\geq$3) deployed on UAV in the system. Finally, the mean error of 0.04m and 2.5° were obtained with low localisation latency through commercial off-the-shelf RFID equipment. On the other hand, instead of localising UAV itself, the other UAV navigation system was also designed by the same research group [52],where the navigation was achieved with the localisation of UAV handheld controller. In this system, the passive RFID nodes were deployed on UAV controller. With the same computation method, the 6-DOF pose of the UAV controller could be calculated. Finally, the control commands will be generated from the controller's pose and sent to UAV for navigation in indoor environment. Even high accuracy and low latency localisation can be achieved as aforementioned. Owing to the inherent characteristics of RFID, the systems are still vulnerable to NLOS path and the localisation coverage range is limited by the communication range of RFID readers. Therefore, the aforementioned systems are only suitable for short range and free space UAV positioning or navigation. Differently, Choi et al. [53] and Longhi et al. [54] both designed the passive Ultra-high Frequency (UHF) RFID based UAV positioning system with RFID reader deployed on UAV. In the localisation process, the communication between RFID reader on UAV and reference RFID nodes embedded on the floor and plant vases was exploited to measure RSS information for UAV positioning. Finally, the authors in [54] declared that a decimetre-level accuracy could be garnered. However, performance of these two approaches is still vulnerable to NLOS path and localisation coverage is still restricted.

2.5 UWB based Localisation System

The UWB is known as a sequence of impulse radio utilising ultra-wideband. It offers the enormous development opportunities in radar, safety and position applications [55]. Different from the narrowband signal, with the ultra-wideband and impulse radio, it is possible to transmit the signal with extremely short duration time (0.20ns-1.5ns) where a high temporal resolution can be achieved, also showing the robustness to multipath fading [56]. Moreover, a short duration time means a low transmit power. Therefore, the low energy consumption will be another key feature for the UWB, in contrast to other UAV localisation technologies. But compared with other radio communication technologies, the energy consumption of UWB still keeps high. Considering the visible characteristics of UWB, it becomes a reliable and feasible localisation technology which has drawn lots of attention for UAV positioning in the past few years [6, 57–75]. Among them, the group from Nanyang Technological University is the most in-depth research group in this area. Up to now, they have already published 9 papers on UAV localisation with UWB within 4 years [57, 59, 65–70, 74].

According to the method for localisation, our review will be given in three parts. The first part will be auxiliary localisation where localisation is achieved with known position and fixed anchor nodes. The system proposed in [6, 57–64] all utilised the communication between tag node deployed on UAV and fixed anchor nodes for UAV localisation. Among them, in [57–59], the conventional Two-way Time of Flight (TW-TOF) approach was exploited to calculate the time delay between tag node and anchor nodes. Meanwhile, velocity and displacement information gathered by IMU was also taken into account which fused with the aforementioned information by EKF to improve the localisation accuracy and keep the reliability. Moreover, authors in [57] also proposed a calibration and outlier detection method through the linear regression and calculation of Mahalanobis Distance [76] which was utilised for UWB information calibration and unreasonable data detection. Unlikely, the authors in [59] mainly focused on anchor self-localisation which leveraged the Non-linear Regression (NLR) achieved anchor self-localisation and position calibration. Finally, decimetre-level accuracy was garnered for all these three systems, especially for [57], the average position error in x–y plane of 0.071 m and the maximum error of 0.2m within $7 \times 7m$ GPS-denied area were obtained. To further improve the accuracy, authors in [60–62] all focused on the accuracy improvement through the mitigation of clock drift. Where the hybrid approach based on MDS, loosely-coupled EKF and Double-sided Two-way Ranging (DS-TWR) was proposed in [60]. Symmetric Double-sided Two-way Ranging (SDS-TWR) was exploited in [61] and [62] for clock drift mitigation. Differently, You et al. [63] applied Unscented Kalman Filter (UKF) to avoid neglecting the high-order terms of the nonlinear observation equation for performance improvement. On the other hand, UWB based UAV localisation systems with TDOA localisation mechanism were designed in [6] and [64], in order to reduce the communication cost compared with TW-TOF, DS-TWR and SDS-TWR. In their systems, UAV position can be calculated directly through the broadcast signal from tag node on

UAV. Detailed information about the localisation principle for each localisation mechanism will be given in Section 3.4.

To remedy the requirement of fixed anchor nodes, the approaches which leverage the communication between multi-UAVs for relative localisation emerge in recent years. In [65, 66], a relative localisation approach was designed for relative localisation and formation control of multi-UAVs. In their system, the accurate distance and displacement information measured by UAV in different position through UWB and IMU were applied for UAV relative initial position estimation. Afterwards, the relative position between UAVs could be calculated through EKF, where the estimated initial position was utilised as the initial input of EKF. According to their simulation and experiment results, the system was capable of meter level relative localisation and formation control. However, an appropriate trajectory for UAV needs to be defined to preserve the performance, including the nonlinear path and piecewise linear path. Length and shape of the trajectory all have huge impact on the different extent of localisation performance. Further development has been done in [67–69] from the same research group. In the new system, the requirement of appropriate trajectory was no longer needed. Instead, they exploited UWB and IMU to measure the distance and velocity information for UAV itself, also leveraged information exchange between dynamic UAVs to obtain the precise relative position for UAV swarm through graph theory based approach. The algorithm could finally achieve decimetre-level accuracy according to their experiment results. On the other hand, another cooperative localisation approach was presented by the same group [70]. They proposed two different methods called Covariance Intersection (CI) and Linear Consensus (LC) based filter achieved the cooperative localisation by information exchange and states estimation with only one landmark. Cao et al. [71] also designed a UWB based relative localisation system which equipped all the anchor nodes on leader UAV to localise the follower equipped with tag node for formation control of UAV swarm. Likewise, the authors in [72] designed the same UWB based localisation system which deployed four anchor nodes on ground station (vehicle of a military convoy) to navigate UAV.

Finally, in order to improve the localisation accuracy and coverage, sensor fusion methods which combined UWB with different types of vision-based localisation approaches have been presented. In [73], RGB-D sensing was combined for mapping and localisation of UAV to implement long-term autonomous operation. In [74], an integrated UWB-Vision system was put forward to achieve the autonomous landing for UAV on moving target. Where UWB, IMU, Optical-flow and Vision were all integrated help for approaching and landing on the moving target. Tiemann et al. [75] also designed a UWB-Vision approach which integrated UWB with monocular SLAM [77, 78] to improve system performance and increase localisation coverage.

2.6 Summary and Discussion on the RF based UAV Localisation Systems

A summary and discussion for pros and cons of the existing RF based UAV localisation systems with different radio communication technologies are given in Table 4. Among them, UWB based systems attract lots of attention on precise UAV positioning which has already published 20 papers in the last five years, owing

Table 4 Comparison for the existing RF based UAV localisation systems with different radio communication technologies

	Advantage	Disadvantage	Existing Literature
Wi-Fi	Implementation simplicity, large coverage, high transmission rate	High energy consumption, meter-level accuracy, vulnerable to NLOS path	[21–24]
Bluetooth	Implementation simplicity, low energy consumption	Small coverage, low transmission rate, vulnerable to NLOS path	[36–38]
Zigbee	Extremely low energy consumption, low system cost	Low transmission rate, high latency, vulnerable to NLOS path	[48]
RFID	Extremely low energy consumption, implementation simplicity, low system cost, high accuracy with specific approach	Small coverage (1m-5m), vulnerable to NLOS path	[51–54]
UWB	High accuracy, extremely high transmission rate, low latency, immune to interference, robustness to NLOS path	High energy consumption and system cost compared with other radio communication technologies	[6, 57–75]

to the characteristics of high accuracy, low latency and robust to harsh environment. Moreover, considering the superiority of UWB, sensor fusion approaches which combine UWB with Vision, IMU or other localisation technologies emerge in recent years are also valuable for further research in this area.

3 Classical Localisation Mechanisms

In this section, a detailed review for the classical localisation mechanisms including RSS, AOA, TOF/TOA, TDOA and Fingerprint etc. with RF based UAV localisation systems are presented. Meanwhile, the capability, suitability and challenges for each on UAV positioning are also summarised by the end of this section.

3.1 RSS based Localisation Mechanism

The RSS is known as the field intensity of a signal measured at the receiver [13]. With the measured RSS, it is simple to quantitatively derive the signal attenuation and calculate the transmission distance followed by an appropriate signal propagation model. Subsequently, position information can be estimated with trilateration or multilateration by the transmission distance. The propagation model given by [79] is shown in Eq. 1, and Fig. 5 gives the schematic diagram of the RSS based localisation mechanism.

$$P_2 = P_1 + 10logK - 10\gamma log\frac{d_{21}}{d_0} + n \tag{1}$$

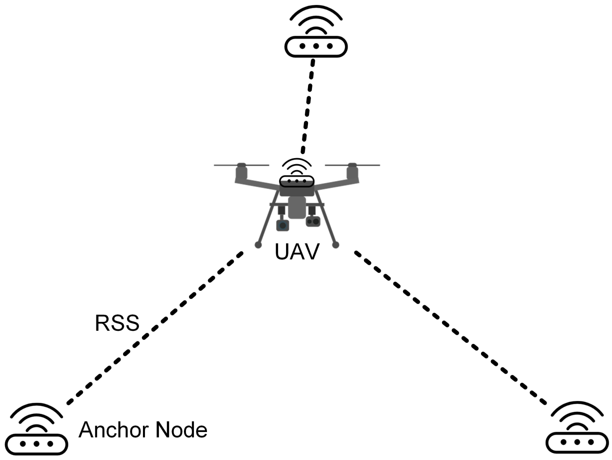

Fig. 5 RSS based localisation mechanism

Where d_{21} represents the calculative distance between receiver and transmitter, P_2 and P_1 are assumed as the signal power at each of them, K is a constant determined by antenna gain and reference distance d_0, γ represents the path loss factor, n is the measurement noise for RSS which is commonly known as Additional White Gaussian Noise (AWGN) with zero mean and variance of σ^2.

As recording RSS is the basic function for almost all the communication devices in nowadays. RSS based localisation mechanism becomes the simplest implementable mechanism among RF localisation technology. However, in actual applications, especially in GPS-denied environment, wireless signal is much more vulnerable to external environmental disturbance, such as occlusion, multipath effect etc. Meanwhile, signal attenuation changes continually with environment variable or media change. Hence, RSS based localisation mechanism is not suitable for UAV localisation in harsh or dynamic environment. However, thanks to cost saving and implementation simplicity features, RSS based localisation mechanism still draws lots of attention in open environment.

As aforementioned in Section 2, RSS based localisation mechanism has already been widely used on UAV localisation. In [21], a UAV position estimation and collision avoidance system were designed which analysed coloured noise in RSS measurement to improve system accuracy. Masiero et al. [22] exploited RSS from nodes communication with linear KF for localisation which successful reduced the computational complexity and improved the operation time of UAV. Zhou et al. [36] utilised RSS measured by Bluetooth beacons achieved UAV navigation in GPS unstable environment. Yu et al. [48] exploited RSS measurements collected by Zigbee nodes as the input of EKF achieved decimetre localisation accuracy. Cheng et al. [80] designed a NLOS detection strategy for mini-UAV localisation system which analysed RSS measurement model to identify propagation condition for NLOS detection to improve localisation accuracy. Tovkach et al. [81] proposed an RSS based localisation approach for UAV with unknown transmit power. Soria et al. [37] and Coppola et al. [38] all designed the relative localisation approaches, applied relative distance from RSS with additional odometry and altitude measurements achieved relative localisation of UAV swarm.

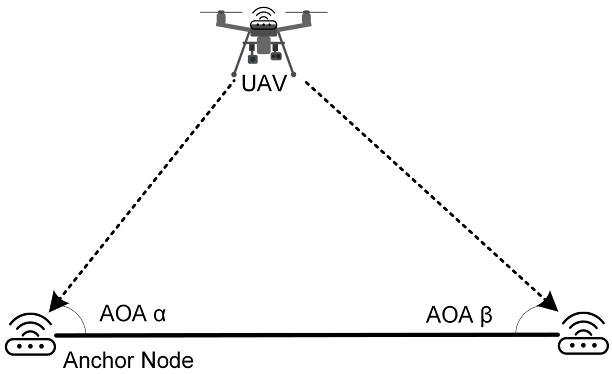

Fig. 6 AOA based localisation mechanism

3.2 AOA based Localisation Mechanism

The AOA, denoted here as the Angle of Arrival, also known as the Direction of Arrival (DOA), is the localisation mechanism which exploits the angle information recorded at multiple receivers for positioning. As shown in Fig. 6, with the AOA information from antenna array and the prior location information of anchor nodes, UAV position can be estimated through the triangulation. Clearly, with the AOA based localisation mechanism, the minimum number of anchor nodes for localisation can be reduced which can expand the application scenario of UAV. Moreover, the traditional RF based localisation system only provides position information. However, it is possible for the AOA based localisation mechanism to provide the 6-DOF state information which have great significance for UAV positioning. Owing to the existing characteristics, several scientific researches have been conducted for UAV localisation with the AOA based localisation mechanism.

Pavlenko et al. [82] proposed a 16-element sparse dome array for UAV localisation based on AOA localisation mechanism where 1σ-values of less than 2° was achieved. For further research, they also developed another localisation system for UAV via radar-based Wireless Local Positioning System (WLPS) [83].The experimental results show that the RMSE of the 3D-positioning equals to 36 cm with one anchor node involved, and improved to 31cm with four anchor nodes involved. However, as discussed in their paper, weight of radar unit with the integrated dome array is about 1.78kg, therefore, the operation time of UAV will be influenced greatly. Different from UAV positioning, Nguyen et al. [84] designed an RF-based localisation system focused on the detection and tracking of UAV and its controller with AOA measurements. However, only average error of 12.2° and 12.71m were achieved.

On the other hand, several recent proposed AOA-based high accuracy localisation systems have also been reviewed, considering their potential application to UAV positioning. Spotfi [26] is known as the typical representative which realised decimetre-level localisation accuracy in harsh environment with the precise AOA information. Zhang et al. [85] designed a 3D-localisation system which achieved the median localisation error of 0.78m in indoor environment through AOA based localisation mechanism with commercial off-the-shelf infrastructures. Soltanaghaei

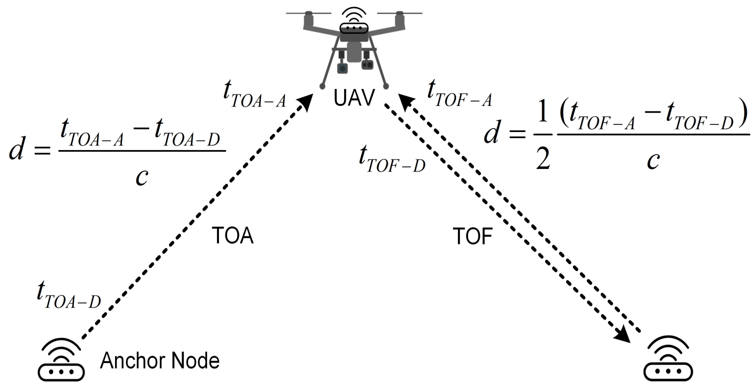

Fig. 7 TOF/TOA based localisation mechanism

et al. [86] proposed a novel localisation approach that realised accurate localisation through multipath of AOA with only one anchor node.

Although, much more advantages of the AOA based approaches can be obtained, there are still many factors that may influence the localisation performance, especially in GPS-denied environment. Owing to the inherent features of the triangulation, even a small measurement error can cause a huge impact on the localisation accuracy with the increasing of transmission distance which will restrict the flight range of UAV. Besides, the system cost, energy consumption and payload of UAV will be increased, considering the additional complex hardware. Most importantly, in dense multipath environment, the AOA estimates are biased in general. So, further research is still needed for the AOA based localisation mechanism on UAV positioning in GPS-denied environment.

3.3 TOF/TOA based Localisation Mechanism

Both the TOF and TOA are the classical time-based localisation mechanisms for the RF based localisation systems. They all exploit the time delay between the transmitter and receiver for range estimation as shown in Fig. 7. With the range information, the UAV positioning can be realised through the trilateration or multilateration. Compared with the RSS and AOA, the TOF/TOA is able to provide the high accuracy performance with no additional equipment required, which is significant for UAV positioning in GPS-denied environment. However, clearly from Fig. 7, the restrict clock synchronisation between all the sensor nodes in the network is required.

To eliminate the impact of clock difference, several different approaches have been proposed [87–89]. The conventional approach is known as Two-way Ranging (TWR) or TW-TOF. As shown in Fig. 8, with the existence of Time of Departure (TOD) and TOA from transmitter and measured response delay on receiver, it is able to subtract clock difference theoretically. Owing to the implementation simplicity and high localisation accuracy (up to centimetre-level accuracy), TWR has already been widely used on UAV positioning in GPS-denied environment [57–59, 63, 65–70, 72]. However, clock drift caused by unpredictable response

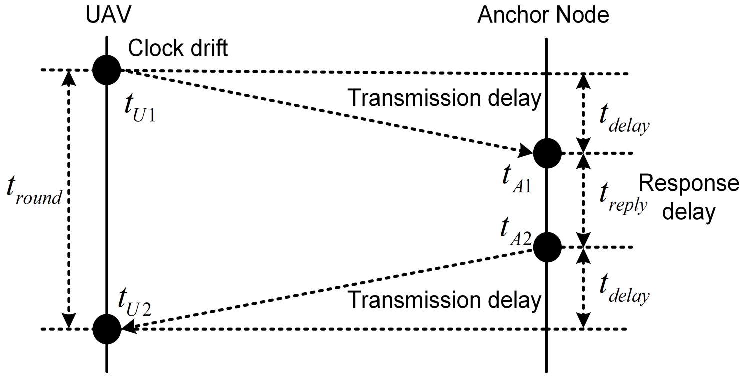

Fig. 8 TWR/TW-TOF based localisation approach

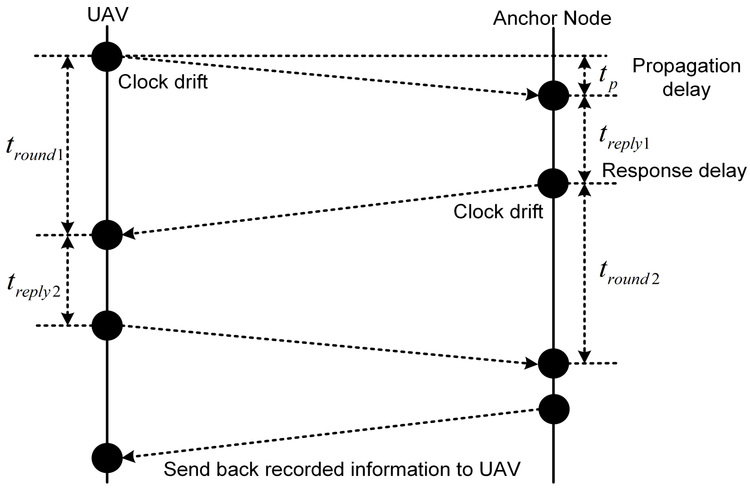

Fig. 9 DS-TWR based localisation approach

delay and low performance crystal oscillator on sensor nodes, will lead to a precision degradation. In addition, with the increasing communication cost, localisation latency and energy consumption cannot be overlooked.

To settle the matter, DS-TWR is proposed. As shown in Fig. 9, the influence of clock drift is mitigated through the average time delay from two-round trip. In [60, 71], DS-TWR has already been applied and tested for precise localisation and formation control of UAV. In addition, for further improvement, SDS-TWR is designed with the similar principle. Compared with DS-TWR, the interval delays are equal on the both participating nodes. Performance of SDS-TWR on UAV localisation has been evaluated in [61, 62], even much more precise result can be garnered, but keeping the same clock frequency on both sides is still difficult to implement. Meanwhile, high accuracy is at the expense of additional communication cost, where position update rate will be significantly restricted which may influence the stability of UAV.

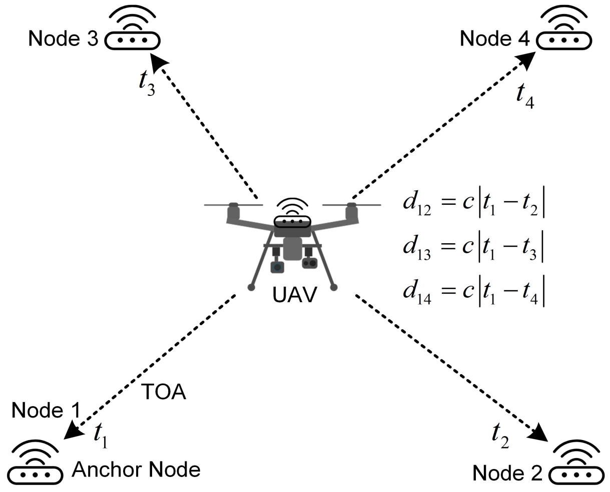

Fig. 10 TDOA based localisation mechanism

3.4 TDOA based Localisation Mechanism

Another classical time-based localisation mechanism widely used on the RF based systems is the TDOA. Different from the TOF/TOA, the TDOA based localisation mechanism utilises the distance difference between each receiver for positioning. Specifically, it leverages the recordings of the TOAs from the broadcast signals by the transmitter to calculate the TDOAs for the localisation through the hyperbolic theorem. As shown in Fig. 10, suppose the distance information between four anchor nodes and UAV are $d_i (i = 1, 2, 3, 4)$. Thus, the distance difference can be calculated and represent as d_{ij}. With the known position information $\boldsymbol{p_i}$ for each anchor node and the record TOAs t_i, position information $\boldsymbol{p}$ of UAV can be estimated through the localisation equation below:

$$\begin{cases} \|\boldsymbol{p_1} - \boldsymbol{p}\| - \|\boldsymbol{p_2} - \boldsymbol{p}\| = c(t_1 - t_2) \\ \|\boldsymbol{p_1} - \boldsymbol{p}\| - \|\boldsymbol{p_3} - \boldsymbol{p}\| = c(t_1 - t_3) \\ \|\boldsymbol{p_1} - \boldsymbol{p}\| - \|\boldsymbol{p_4} - \boldsymbol{p}\| = c(t_1 - t_4) \end{cases} \tag{2}$$

Since only the time difference from each sensor node is enough for precise positioning, the localisation latency and energy consumption of the TDOA based localisation mechanism can be reduced greatly compared with the TOA and TOF, which can effectively improve the stability and flight time of the UAV in GPS-denied environment. Considering the existing characteristics, different localisation systems have already been designed for UAV positioning with TDOA based localisation mechanism. Tiemann et al. [6, 90, 91] carried out a series of scientific researches on TDOA based localisation mechanism to achieve precise localisation for multi-UAVs and mobile robots. Likewise, the authors in [92] designed a localisation system which successfully implemented the stable control of UAV in GPS-denied environment with measured TDOA and EKF. Sinha et al. [93] and de Sousa et al. [94] both did related researches for UAV localisation through TDOA. But, not mainly focused on UAV localisation in GPS-denied environment. Sinha et al. [93] intended to analyse the impact of 3D Antenna Radiation Patterns through TDOA based localisation for UAV. The authors in [94] mainly concerned the precise localisation of UAV in urban area with a full of NLOS path. They exploited ray-tracing fingerprint build from TDOA to identify the main obstacle reflected signal as virtual anchor to achieve precise localisation for UAV in NLOS scenario.

Despite precise and low latency localisation is able to achieve through TDOA based localisation mechanism, there are still several factors that may restrict the performance. Obviously, since TOAs are measured by different anchor nodes, precise synchronisation is required between all these receivers. Similar to other time-based approaches, TDOA is also vulnerable to the time-delay caused by NLOS path and measurement noise. In addition, considering applications on UAV, localisation process is conducted by receiver or localisation server for TDOA based localisation mechanism. Therefore, an extra step is required to send back the estimate position to UAV, which may cause position lost or low update rate due to the potential signal block or interference.

3.5 Fingerprint based Localisation Mechanism

Considering that the RSS based localisation mechanism requires prior information, deviates dramatically with the existence of the NLOS path and external interference, is vulnerable to environment variations and measurement noises. Another method which extracts the features from fingerprint dataset built with RSS or other radio information from the surrounding nodes for positioning is designed. The localisation process of the fingerprint-based localisation mechanism is composed of offline and online phases. In the offline phase, the RSS and other radio information from the different location will be recorded to establish the fingerprint database. Then, in the online phase, the measured information from UAV will be compared with the fingerprint database for localisation.

Owing to the implementation simplicity, acceptable accuracy and ability to construct radio map help for collision detection, fingerprint attracts certain attention on UAV applications. But most of the proposed approaches are focused on node detection through UAV with the existence of GPS in unknown environment, only few of research pays attention to localise UAV itself. In [95], an indoor localisation system called a High-speed Quadrotor Localisation (HiQuadLoc) system was designed, which successfully kept stability of UAV in indoor environment with RSS fingerprinting. In their system, a 4-D RSS interpolation scheme was proposed which added RSS sample space to mitigate site survey overhead for reducing the requirement of training data volume. Finally, successfully reduced localisation latency, restrained the effect of high-speed movement, reduced the number of RSS sampling and improved the localisation accuracy. In addition, another fingerprint-based UAV localisation system proposed in [96] still focused on the offline process. Where tensor completion was exploited to achieve the time reduction of data collection and training process in offline phase.

As discussed, the characteristics of fingerprint, including implementation simplicity, high accuracy (decimetre-level) and ability to construct radio map all make it suitable for UAV localisation. However, owing to the demand for large volume of data and vulnerable to dynamic environments, there will be an upsurge of corresponding computational overhead and instability of localisation. Consequently,

Table 5 Comparison for the existing RF based UAV localisation systems with the classical localisation mechanisms

	Advantage	Disadvantage	Existing Literature
RSS	Implementation simplicity, cost efficient	Low accuracy, vulnerable to NLOS path and environment variables	[21, 22, 36–38, 48, 80, 81]
AOA	High accuracy with specific algorithm, able to provide orientation information, immune to location ambiguity	Vulnerable to measurement noise and NLOS path, require additional equipment, high energy consumption, high system cost	[82–84]
TOF/TOA	High accuracy with specific algorithm, low computational complexity	Synchronisation between all sensor nodes required, high communication cost, low update rate, vulnerable to response delay, vulnerable to NLOS path	[57–63, 65–72]
TDOA	High accuracy, low communication cost, low latency	Synchronisation between anchor nodes required, vulnerable to NLOS path, high computational complexity	[6, 92–94]
Fingerprint	Implementation simplicity, high accuracy, ability to construct radio map help for collision detection	Large volume data required, vulnerable to dynamic environment, high computational complexity	[95, 96]

fingerprint based localisation mechanism is not suitable for UAV localisation in dynamic and unknown environment.

3.6 Summary and Discussion on the Classical Localisation Mechanisms

A summary and discussion for the pros and cons of the classical localisation mechanisms with RF based localisation systems on UAV positioning is given in Table 5. Among them, time-based localisation mechanisms including TOA/TOF and TDOA attract lots of attention due to the high localisation accuracy. Besides, according to our investigation, there are also lots of researches on RSS based localisation mechanisms considering the cost efficient and implementation simplicity features. But mainly focused on the applications in open environment.

4 Evaluation Framework for UAV Positioning with RF based Localisation Technologies in GPS-denied Environment

To the authors' best knowledge, the evaluation framework considering both the RF based localisation technologies and UAV positioning in GPS-denied environment is currently missing from the literature. However, quantifying system performance and in-depth analysis for the key factors of the system are important and can be the guidance for subsequent research. Therefore, in this section, we will elaborate and analyse the KPIs for UAV positioning with the RF based localisation technologies in GPS-denied environment and establish the evaluation framework.

4.1 Localisation Accuracy (LA)

Localisation accuracy is commonly known as the disparity between the estimated position information and the ground-truth. Apparently, it is the conventional and essential index for all the location-based applications or systems. In a general sense, a higher accuracy represents a greater performance. However, under different applications, the acceptable accuracy will be varying. For instance, for precision machining, even millimetre-level localisation accuracy is insufficient. But meter-level is enough for rescue mission in mining industry. Thus, considering the operational environment in this paper where GPS is unavailable such as oil pressure vessel, warehouse or mine cave, and in order to keep the stability and avoid the collision of UAV, the decimetre-level accuracy is desired. In some extreme cases, such as the place full of obstacles or confined space, the centimetre-level accuracy is also demanded.

4.2 Localisation Latency/ Update Rate (L/U)

Real-time or low latency localisation means the system can calculate reliable localisation results without any noticeable delay. It is often known as one of the indexes to evaluate localisation performance. Generally, the traditional indoor localisation systems are not sensitive to the localisation latency less than second-level. However, for UAV positioning, localisation latency will significantly affect the position update rate of UAV. Considering that UAV is always in motion even when hovering, a lower update rate or higher localisation latency will cause a greater gap between each posture adjustment command, where unstable flight may happen. Thus, the update rate is always one of the most concerned indicators to measure the performance of commercial UAV positioning system. In the design of high-performance localisation algorithm for UAV application, the localisation latency also needs to be considered which can be denoted as the low computational complexity for the algorithm.

4.3 Stability in Different Environment (SDE)

Compared with the outdoor environment, the applications in GPS-denied environment are more complicated and vulnerable to multipath fading and the NLOS path caused by the unpredictable objects or people. These will lead to the precipitous decline or violent fluctuation of the localisation accuracy. In addition, the unreasonable value is more easily to occur which may derive a non-smooth result. This precision degradation and fluctuation may cause the unstable flight of UAV or increase the crash down probability. Therefore, the environmental adaptability will be the particular index for UAV applications in GPS-denied environment.

4.4 Auxiliary Equipment Requirements (AER)

Traditional RF based localisation systems often require the existence of anchor nodes with known location. As above mentioned, the conventional trilateration and multilateration localisation algorithms demand at least three anchor nodes to locate the target. However, considering the applications for UAV in GPS-denied environment, the difficulty to deploy anchor nodes or measure the precise location of these nodes will become the problem to be remedied. Therefore, the demand degree for the auxiliary equipment will be another key index to measure the performance of a RF based UAV localisation system.

4.5 Weight/Size (W/S)

Different from other applications, the payload of UAV is extremely restricted. The loading condition of UAV also have the close connection with the operation time of it. The AOA based localisation mechanism has proven to achieve decimetre-level accuracy and provide the 6-DOF position information [26, 83]. However, the size and weight of the additional antenna array will restrict the applications on UAV. Thus, the weight and size of the localisation components becomes another particular index for UAV positioning.

4.6 Localisation Coverage (LCR)

The localisation coverage for RF based system is commonly treated as the communication range of sensor nodes which has a huge impact on the operating range of UAV. It is varying under different wireless communication protocols. Besides, higher localisation coverage is also achievable with additional anchor nodes. However, the application scenario will be restricted, due to the demand for the prior location of anchor nodes. Therefore, the balance between localisation coverage and auxiliary equipment requirements need to be considered when designing the RF based localisation system for UAV.

4.7 Energy Consumption (EC)

Energy consumption is always one of the primary indexes when evaluating the performance of a RF based localisation system. For traditional applications, considering the charging difficulty of tag nodes, low energy consumption often means the system is capable to keep the tag nodes alive for months or years with ordinary batteries, which makes BLE, Zigbee and passive RFID received lots of attention. However, for UAV positioning, there is no need to consider the circumstances that difficult to charge sensor nodes or keep them alive for months. Keeping sensor nodes alive during the operation process and having no impact or little impact on the operation time of UAV is enough.

4.8 System Cost (SC)

Low-cost system which can easily penetrate the consumer market and be widely adopted is always the development direction for robotic technologies in modern society. In addition, considering the UAV applications in GPS-denied environment, it is much more vulnerable to the unpredictable damage like crash down or control failure. Therefore, it is necessary to consider the system cost for designing the RF based UAV localisation system in GPS-denied environment.

4.9 Demand level discussion under different application scenarios

To further analyse the key factors for UAV positioning, the discussion for the demand level of each has been made according to the application scenarios. Considering it is difficult to define or provide a very specific value suitable for all the applications, only a demand level for general applications is provided. The application scenarios of UAV in GPS-denied environment are divided into six areas, including indoor or confined space inspections, mining, bridge inspections, search and rescue, critical infrastructure and surveying disaster sites [97]. The demand level for each indicator under these application scenarios have been analysed and summarised as follow.

- Indoor or confined space inspections: Considering the application for indoor or confined space inspections such as the corrosion detection for oil pressure vessel or water tanks, UAV needs to fly close to the wall for a detailed inspection. Thus, the KPIs including LA and L/U will be particularly important in case of any collision and prevent the unexpected drift in the flight area. Furthermore, the flight environment under this application scenario is relatively fixed during the operation process of UAV. Therefore, the demand level for AER and LCR will remain low.
- Mining: Similar to the application for smart inspection, in case of any potentially harmful for the components and miner in the narrow space inside a mine, the LA and L/U will be particularly important. But differently, the miner or equipment inside the mine will make the environment become cluttered, which means a higher accuracy to the centimetre-level is desired in some extreme cases, and the SDE becomes significant for the applications under this circumstance.
- Bridge inspections: Another popular application for UAV in GPS-denied environment is bridge inspections. The inspector often utilises UAV to fly underneath bridges to inspect the corrosion, paint loss and rust which is hard to detect with the traditional methods. Clearly, the same as the previous applications, the flight area of UAV under the bridges is sorely limited. The flight environment is relatively fixed during the whole process. Thus, the LA and L/U are still the most important factors. The demand level for the SDE, AER and LCR will all remain low.
- Search and rescue: Different from all the aforementioned applications, the search and rescue mission will pay more attention to search and fast locate the salient entities within an unknown and relatively spacious environment [98]. Thus, the SDE, AER and LCR will become significant, and the fluctuation for the LA within the meter-level and low update rate are all acceptable.
- Critical infrastructure: In the consideration of the security risks of GPS, in some restricted area such as military bases or power plants, soldiers or engineers often utilise UAV without GPS for monitoring. The application scenarios in these areas can be supposed as a fixed, open and large environment. Therefore, the LCR for the localisation system is turned to be the most concerned factor.

Table 6 Analysis of current RF based UAV localisation systems under the proposed evaluation framework

System	Type	LA	L/U	SDE	AER	W/S	LCR	EC	SC
[21]	Wi-Fi/RSS	Meter	10Hz	L	M	L	M	M	L
[22]	Wi-Fi/RSS	Meter	N/A	L	H	L	M	M	M
[23]	Wi-Fi/RSS	Meter	N/A	L	M	L	M	M	L
[24]	Wi-Fi/RSS	Decimetre	N/A	M	H	L	M	M	M
[36]	Bluetooth/RSS	Meter	N/A	L	H	L	L	L	L
[37]	Bluetooth/RSS	Decimetre	N/A	L	N/A	L	L	L	L
[38]	Bluetooth/RSS	Decimetre	5Hz	L	N/A	L	L	L	L
[48]	Zigbee/RSS	Decimetre	N/A	L	M	L	L	L	L
[51, 52]	RFID	Centimetre	50Hz	L	M	L	L	L	L
[54]	RFID/RSS	Decimetre	N/A	L	H	L	L	L	L
[6]	UWB/TDOA	Centimetre	40Hz	M	M	L	L	M	M
[57]	UWB/TWR	Centimetre	40Hz	M	M	L	L	M	M
[58]	UWB/TWR	Decimetre	80Hz	M	M	L	L	M	M
[59]	UWB/TWR	Decimetre	20-250Hz	M	M	L	L	M	M
[60]	UWB/DS-TWR	Decimetre	200Hz	M	M	L	L	M	M
[61]	UWB/SDS-TWR	Decimetre	N/A	M	H	L	L	M	M
[62]	UWB/SDS-TWR	Centimetre	65-372Hz	M	H	L	M	M	M
[63]	UWB/TWR	Centimetre	N/A	M	M	L	L	M	M
[65, 66]	UWB/TWR	Meter	20Hz	M	L	L	M	M	M
[67–69]	UWB/TWR	Decimetre	N/A	M	N/A	L	M	M	M
[70]	UWB/TWR	Centimetre	N/A	N/A	L	L	L	M	M
[71]	UWB/DS-TWR	Decimetre	N/A	M	N/A	L	M	M	M
[72]	UWB/TWR	Decimetre	6.5-12ms	M	M	L	M	M	M
[73]	UWB/RGB-D	Decimetre	N/A	L	M	M	M	M	M
[74]	UWB/Vision	Decimetre	N/A	L	M	M	M	M	M
[75]	UWB/RGB-D	Decimetre	32Hz	L	M	M	M	M	M

– Surveying disaster sites: The same as the applications for search and rescue, the most challenging part for surveying disaster sites will be the unknown environment and unpredictable obstructions, which makes the SDE, AER and LCR become significant.

4.10 Evaluation and Analysis on the Existing RF based UAV Localisation Systems

Finally, a comprehensive evaluation and analysis for the aforementioned RF based UAV localisation systems with different radio communication technologies under different localisation mechanisms is given in Table 6, utilising the established evaluation framework. Where, L represents low, M is assumed as medium, H means high, N/A indicates not applicable or never mentioned in the paper. Here need to indicate that L/U for [21, 65, 66, 72] are the distance measurement update rate, the localisation latency or position update rate is not mentioned in these papers.

To the authors' best knowledge, no system exists which can satisfy all the indicators in the framework. However, each of them has their own advantages under different circumstance. Considering the meter-level accuracy, implementation simplicity, low system cost and large communication range of Wi-Fi based system with the RSS based localisation mechanism, it is much more suitable for the applications in outdoor environment to substitute or compensate the GPS for localisation. Where the authors in [21] and [22] are all utilised the Wi-Fi based UAV positioning system with the RSS based localisation mechanism for the outdoor applications such as search and rescue, exploration and remote sensing. Differently, for the Bluetooth based system with the RSS based localisation mechanism, the communication range is restricted around 10m to keep the performance, but the weight and size of the sensor nodes, the system cost and energy consumption are significantly reduced in contrast to the Wi-Fi based system. Thus, this type of system is more effective for the applications on Micro Air Vehicles (MAVs) or micro-uavs in smaller indoor environment, where both [37] and [38] focused on the applications under this circumstance. Furthermore, the same as the previous conclusion, the low data rate feature of the Zigbee based system may cause the high localisation latency which runs counter to the requirements on UAV. Towards this end, only a few research [48] has been carried out, which means the Zigbee based system is not the ideal choice for UAV positioning. Similar to the Bluetooth based system, the weight and size of the sensor nodes, system cost and energy consumption of the RFID based system also remain low. But differently, the UHF RFID significantly improved the accuracy into the centimetre-level, and the tiny size of passive RFID nodes makes it possible to estimate the orientation information with multi sensor nodes equipped on UAV. However, the restricted communication range and NLOS sensitive characteristic still limit the applications of the RFID based UAV positioning system in smaller and open indoor environments. Finally, we will highlight the UWB based system with the time-based localisation mechanisms here considering the existing characteristics and the application scenarios in this paper. The detailed analysis for each indicator individually will be given as follow to prove our conclusion.

- LA: As mentioned before, high time resolution is able to achieve with extremely short duration time of transmit signal for UWB based system. Thus, decimetre or centimetre-level localisation accuracy is simple to achieve for UWB based system with time-based localisation mechanisms which is extremely important for UAV positioning in GPS-denied environment.
- L/U: For RF based localisation system, the localisation latency is closely related to the data transmission rate of each radio communication technology. Obviously, with the highest data transmission rate, UWB based system can achieve extremely low localisation latency which is much more suitable for UAV localisation compared with other radio communication technologies.
- SDE: With the extremely short duration time of transmit signal for UWB based system, it is much easier to identify the signals from different path which makes UWB based system can resist multipath fading. Therefore, the localisation performance of UWB based system is much more stable than other RF based systems in different operational environment, especially in cluttered environment.
- AER: The requirement for auxiliary components (anchor nodes) is the defect for almost all the RF based localisation technologies. However, with the high data transmission rate and ranging accuracy for UWB based system, it is possible to realise the relative localisation for UAV swarm to get rid of this limitation, as declared in the existing literature [67–70].

- W/S: For UWB based localisation system, the precise localisation is achieved by the compact and light weight wireless UWB sensor nodes, where the weight and size of the sensor nodes only have little impact on UAV [99, 100].
- LCR: As aforementioned, the localisation coverage is related to the wireless communication protocols. Compared with other RF based localisation technologies, even UWB based sensor node is not the one with the widest communication range, but still keep large localisation coverage [99–101].
- EC: Compared with other RF based localisation systems like Bluetooth, Zigbee and Passive RFID, the energy consumption for UWB based system is much higher. But considering the application on UAV positioning, there is no need to keep the sensor node working for months or years, keeping it alive during the operation process of UAV is enough. Thus, even UWB based system is not the one with lowest energy consumption, but still suitable for UAV positioning.
- SC: Due to the special requirements of UWB based system, the system cost is much higher than other RF based systems. But considering the application for UAV positioning in GPS-denied environment, there is no need for large-scale nodes (hundreds of wireless sensor nodes) for localisation. Thus, the system cost of UWB based system can be still kept in low level.

It is concluded that the UWB based system with time-based localisation mechanisms is the best option for UAV positioning with RF based localisation technologies in GPS-denied environment.

5 Current Challenges on UAV Positioning with RF based Localisation Technologies

Under the in-depth discussion and establishment of the evaluation framework for RF based localisation systems on UAV positioning, current challenges for designing or implementing high-performance RF based localisation system of UAV in GPS-denied environment will be discussed in this section to act as the guidance and lay fundamental base for subsequent research.

5.1 NLOS Error

One of the fundamental challenges for precise localisation of UAV with RF based technologies in GPS-denied environment will be the abominable communication environment. It is always difficult to assess the communication condition, considering the dynamic characteristics of the working environment. Owing to the inherent nature of electromagnetic waves, to avoid reflect, refract and diffract of the communication signal between sensor nodes is impossible [15], that is where NLOS error comes from. NLOS error here denotes the localisation error caused by NLOS communication between sensor nodes, also treated as the excessive travelling distance. To be specific, the reflection or refraction of the signal will lead to the additional power loss, additional time-delay or incident angle change which all have the significant consequence on localisation accuracy. Moreover, the multipath fading caused by the NLOS communication will also make it challenging to distinguish the direct path. To remedy this, plenty of approaches have been presented.

According to the method of dealing with NLOS error, these approaches can be divided into two categories, NLOS identification and NLOS mitigation.

The NLOS identification means to identify the NLOS path or measurement which are influenced by the NLOS error. In the last decade, hundreds of approaches have been developed in this area. The traditional approaches utilised the building methods or model and the existing LOS information to identify the NLOS path through the measured distance, signal strength or channel characteristics. The identification accuracy is relevant to the building methods or model and the existing LOS information. Differently, the Artificial Intelligence (AI) based approach first utilises the RSS or Channel State Information (CSI) training data for feature extraction, then it is to distinguish the NLOS path. Even no identification model is required, however, the performance is restricted by the data volume. In this part, a brief overview for these two different NLOS identification approaches will be given.

In [102], Chan et al. proposed an identification approach to identify NLOS path through the designed residual test with measured TOA and successfully achieved over 90% accuracy. However, performance of the algorithm is restricted by the number of the base stations (anchor nodes) and LOS dimension for these nodes. The performance will drop sharply in terms of lack of LOS anchor nodes or if LOS dimension is under 4. Differently, another approach was proposed in [103] which exploited TOA-DOA fusion to precise identify NLOS nodes and improve accuracy with reflection points served as reference nodes. In this approach, TOA and DOA from the same target measured by different anchor nodes were applied to estimate multi-group position information, then to analyse estimation bias for distinguishing NLOS and LOS nodes. Moreover, a shared reflection point identification and localisation algorithm was presented to improve the positioning accuracy. However, their approach has the assumption that all reflection must be single bounce. Besides, the performance will be greatly restricted by accuracy of DOA and synchronisation between nodes. Similar to the above method, Zhang et al. [104] designed another approach which also utilised the measured angle information to transform the reflection points as reference nodes for localisation. Differently, this method could identify the multi reflection point through calculated possible region for target node from measured AOA, Angle of Departure (AOD) and TOA information. However, unless at least one single bounce reflection exists, the proposed approach is unable to identify multi reflection points. Besides, not only AOA, but also AOD is required which means for both target and anchor nodes high-performance antenna arrays are required to preserve the accuracy.

On the other hand, some other approaches exploiting machine-learning or deep-learning for precise identification were also proposed. The authors in [105] applied the non-parametric machine learning techniques for identification with no need of statistical characterisation for LOS and NLOS channels. Six different features were extracted directly from received waveform for classification through Least Square Support Vector Machine (LS-SVM), owing to the characteristics of robustness, few requirements of user-defined parameters and superior performance. Due to the huge computational complexity of Support Vector Machine (SVM), Relevance Vector Machine (RVM) was exploited in [106] to identify and mitigate NLOS error with lower computational cost. They declared that an extremely smaller number of Relevance Vectors (RVs) of RVM were utilised for classification than Support

Vectors (SVs) of SVM. Moreover, compared with SVM, RVM is able to estimate error bar for the improvement of localisation accuracy. In order to further reduce computational complexity, Yang et al. [107] proposed another NLOS identification approach based on Import Vector Machine (IVM). During identification process, a feature selection strategy was designed to select optimal feature from the same six features to improve accuracy and reduce computational complexity. Moreover, comparison of SVM and RVM with proposed approaches was made to evaluate the effectiveness. In order to exclude human intervention, deep-learning based approaches for NLOS identification emerge recently. Bregar et al. [108] presented a Convolutional Neural Network (CNN) based approach exploiting measured raw CIR for precise identification. The dimensionality of CNN was also reduced by filtering useful training data as small batches to significantly lower the complexity and improve the robustness of the algorithm. On the other hand, considering the insufficient information from single measurement and limitation of CIR, Choi et al [109] proposed another approach which applied a series of CSI to further improve the identification efficiency and accuracy by aid of Recurrent Neural Network (RNN). However, all these data-aided methods are susceptible to unknown or dynamic environment due to the requirement of plenty measurements and training process for feature extraction. Moreover, for UAV applications, on-board identification is unrealistic owing to the limit power supply and high computational complexity. Therefore, further research is still necessary.

Compared with NLOS identification, NLOS mitigation is able to remedy the lack of LOS anchor nodes problem to eliminate the influence of NLOS. The authors in [110] proposed two different convex relaxation approaches called as the Semidefinite Relaxation (SDR) and the Second-order Cone Relaxation (SOCR) to mitigate the NLOS error precisely with the ability for solving non-convexity problem. They successfully mitigated NLOS error from measured TOA with no need of plenty statistical information. In addition, they also extended the above method to TDOA based localisation approach in [111]. At the same time, Marano et al. [105], Van Nguyen et al. [106] both designed the approach for NLOS error mitigation after identification with SVM and RVM. However, there is still restriction for NLOS mitigation. When compared with the identification approaches that remove NLOS nodes directly, mitigation approaches can only approximate LOS condition even in the ideal case. Therefore, NLOS mitigation approaches are only suitable for the applications with less LOS node exists.

5.2 Node Synchronisation

Generally, in the ideal case, the clocks on all the sensor nodes are identical. However, considering the material, structure and manufacturing process, the clock of each sensor node is different. Additionally, to limit the system cost, the only low performance crystal oscillator can be provided for the wireless sensor nodes of the RF based localisation system. Therefore, with the extremely fast speed of electromagnetic waves, even a small difference between the local clock will have a huge impact on the localisation accuracy, especially for the time-based localisation mechanisms. Hence, precise synchronisation will be the other grand challenge for precise localisation of UAV with RF based systems.

The current synchronisation approaches can be classified based on the method for handling the clock difference. One is to cancel out the clock difference through communication strategy or regulate clock difference with additional synchronisation server or node. The other is to achieve the relative synchronisation with the estimation of clock difference. As above mentioned, the localisation approaches such as TWR, DS-TWR and SDS-TWR all are synchronisation free which cancel out the clock difference by multi communication. However, the additional problems will be raised, like response delay, communication cost and high latency. The other conventional approach is leveraging additional synchronisation server or node to regulate clock difference. Lots of classical protocols or strategies on this side have been proposed over the past decades like Timing-sync Protocol for Sensor Networks (TPSN) [112], Flooding Time Synchronisation Protocol (FTSP) [113] and Reference-broadcast Synchronisation (RBS) [114] which are summarised in [115–118]. Nevertheless, performance for these approaches will be restricted by synchronisation server or node itself, also by the communication condition and synchronisation strategy. Meanwhile, with the extra components, energy consumption will also be the burning issue. Therefore, in this paper, we will mainly focus on the relative synchronisation with the estimation of clock difference. The classical approach was proposed in [119] which leveraged two-way exchange successfully estimate clock difference between sensor nodes with the known time delay. However, only clock offset is taken into account. For further research, authors in [120] designed a synchronisation protocol called Asymmetrical Time-stamping and Passive Listening (ATPL) utilised the same two-way exchange strategy. Differently, passive listened message from other nodes was considered to estimate relative clock skew and offset, also to reduce communication cost. However, with the same strategy, even communication cost is reduced, but still keep high-level. Meanwhile, LOS paths between each sensor node are required to keep precise synchronisation. Likewise, Wang et al. [121] proposed another clock skew and offset estimation approach, which also utilised the same strategy and overhearing message. But different from the aforementioned approaches, only two-way exchange between the chosen two sensor nodes is required and no prior position information, response time or transmit time from responder needed. Therefore, communication cost of this approach is significantly reduced. But LOS paths are still required. On the other hand, Xiong et al. [122, 123] proposed another robust clock synchronisation approach which only requires periodic broadcast signal from each anchor node to estimate relative clock skew and offset. Even communication cost is reduced compared with all the aforementioned approaches, but with the additional communication between anchor nodes, LOS path between these nodes must be guaranteed. For further research, Wang et al. [124] proposed a revised synchronisation approach with unknown position information of anchor nodes followed by Xiong's [122,123] work, which is much more suitable for UAV localisation in unknown environment.

5.3 Anchor Self-positioning and Relative Localisation of UAV

One of the fundamental requirements for the traditional RF based localisation systems is adequate anchor nodes with precise location. However, consider UAV application in GPS-denied environment, it is hard to measure the precise position information of anchor nodes before system operation. Under such circumstance, anchor self-positioning turns into one of the most concerned research questions in this area. In [125, 126], a source position estimation approach called Source Position Estimation for Anchor position uncertainty Reduction (SPEAR) was proposed which achieved precise estimation of anchor position with existing RSS measurements. However, prior information for some anchor nodes is still required. Besides, the final estimation error is not acceptable for UAV localisation. Differently, Großwindhager et al. [127] designed a Single-anchor Localisation System using Multipath Assistance (SALMA) for precise localisation. Thanks to the existing geometry for the building and the characteristics of the UWB signal, virtual anchor nodes are able to be built up with reflection between transmitter and receiver for precise localisation. Finally, a median error below 8cm with off-the-shelf UWB sensor node is garnered. However, in dynamic or unknown environment, this approach will lose effectiveness. In addition, another anchor self-localisation approach was proposed in [128] which exploited TOA measurements sequentially gathered from anchor nodes by moving quadcopter by hand and previous robust solvers to estimate anchor position for UAV localisation.

Furthermore, in some extreme circumstance, like the search and rescue mission in unknown environment, it is not only difficult for anchor position measuring, but it is also hard to deploy anchor nodes where self-localisation may lose effectiveness. To remedy this, relative localisation through cooperation of UAV swarm will be a feasible plan. As aforementioned, authors in [67–70] from the same research group proposed the effective relative localisation approaches achieved precise localisation and formation control of UAV swarm with communication between UWB sensor nodes. Likewise, same approaches were presented in [71] and [72], where all achieved relative UAV localisation with anchor nodes deployed on dynamic UAV and military vehicle. However, further development is still required to improve the accuracy and keep stable performance in cluttered environment.

5.4 Signal Block or Interference between Localisation Server or Ground Station and UAV

Currently, there are two patterns for RF based UAV localisation system, the off-board pattern and on-board pattern, as shown in Fig. 2. For off-board pattern, the localisation algorithm will be deployed on an additional localisation server (ground station), which is responsible for the complex computing. Thus, for off-board pattern, the computational complexity and the system energy consumption only have little impact on localisation latency and UAV operation time. However, the additional process to send back the estimated position to UAV is required. Considering the applications in GPS-denied environment, the potential signal interference or block for the additional process may cause the position lost or low position update rate of UAV. Moreover, to avoid signal interference or block between UAV and ground station is not only the primary challenge for precise localisation, but also extremely significant for stable control of UAV.

5.5 Energy Consumption

As aforementioned, different from the off-board pattern, instead of the additional localisation server, an on-board processor will be equipped on UAV which is responsible for position estimation. Apparently, for on-board pattern, the computational complexity of the algorithm and energy consumption of the processor will all have great influence on the operation time of UAV. To lower the energy consumption, lots of approaches through different perspectives have been proposed. However, balance between energy consumption, computational complexity and localisation accuracy to preserve the stability of UAV requires to be take into consideration, where at least decimetre-level accuracy with high update rate should be ensured, then to consider the lowest energy consumption to keep UAV alive for longer time.

5.6 Unreasonable Value

Owing to the unpredictable working environment and communication condition between all sensor nodes. Considering the measurement noise from each sensor node is constantly changing due to the individual difference, the unreasonable value which denotes as the fluctuation of localisation results may occur. Generally, performance degradation caused by unreasonable value is not a sustained impact. Thus, for traditional applications, these values can be ignored directly. However, for UAV positioning, even a short-term position drift can lead to the unstable control. Hence, before reaction of flight controller, localisation results must be smoothed or filtered to eliminate violent fluctuation which makes unreasonable values become to a special challenge for UAV positioning.

5.7 Summary and Discussion on the Current Challenges of the RF based UAV Localisation Technologies

A detailed discussion on current solutions of the challenges for UAV localisation with RF based localisation technologies is provided in Table 7. The advantages and disadvantages for each solution under the consideration of the evaluation framework proposed in Section 4 are also generalised which can give a clear guidance for subsequent research. Moreover, under the comprehensive overview and discussion for the current solutions, the potential research issues for UAV localisation with RF based localisation technologies in GPS-denied environment are generalised as follow to give a clear guidance for future research.

- How to keep accurate NLOS identification with less LOS anchor nodes exist. As discussed, the authors in [102–104] all exploited the anchor nodes which have the LOS communication path to serve as the reference nodes for identification. Therefore, enough LOS anchor nodes are required to keep the accuracy. However, under our application scenario, UAV is more likely to fly in the unknown, dynamic or cluttered environment where deployment of plenty of LOS anchor nodes is difficult to achieve.

Table 7 Discussion on current challenges for UAV positioning with RF based localisation technologies

Current Challenges	Current Solutions	Advantage	Disadvantage
NLOS Error	NLOS Identification: Utilising the inherent rule of each RF signal to find signal changing under different communication path	Stable performance, immune to NLOS path, implementation simplicity	Statistical information required, lose effectiveness with not enough auxiliary nodes
	NLOS Mitigation: With the appropriate mathematical model to mitigate NLOS error	No need for any statistical information or previous data, acceptable accuracy in most situation	High computational complexity, unstable under extreme case
Node Synchronisation	Utilising communication strategy to avoid synchronisation	Implementation simplicity, low computational complexity	Suffering from response delay or clock drift, high communication cost
	Exploiting the additional synchronisation node/server with appropriate synchronisation protocol	Implementation simplicity, acceptable accuracy, low computational complexity	Restricted by synchronisation node/server, high communication cost
	Estimating clock difference for relative synchronisation	No additional components required, acceptable accuracy with specific algorithm	High computational complexity, require LOS path between nodes
Anchor Self-positioning and Relative Localisation of UAV	Leveraging auxiliary nodes for anchor self-positioning	Implementation simplicity, low communication cost	Prior information required, restricted by auxiliary nodes, additional equipment required
	With the appropriate strategy for anchor self-positioning in offline process	No prior information required, no extra equipment required	Deployment of anchor nodes required, high communication cost
	Relative localisation of UAV	No auxiliary nodes required	Prior information for UAV displacement and velocity required, high computational complexity
Signal Block or Interference	Additional auxiliary nodes serve as relay stations	Stable communication condition in harsh environment	Additional auxiliary nodes required, difficult to implement in unknown environment
	Multi-hop communication with specific strategy	No extra equipment required	Unstable performance, high energy consumption
Energy Consumption	Reduce computational complexity and communication cost	No extra equipment required, easy to implement with specific algorithm, low localisation latency	Localisation accuracy degradation
	Additional localisation server	High accuracy and stable performance, no need to consider energy consumption	High latency, suffer from signal block or interference, additional equipment required, high system cost
Unreasonable Value	Identify the unreasonable value with specific algorithm like Mahalanobis distance	No prior information is required, stable performance	High computational complexity, identification fail
	Smooth the result with mathematical model like EKF	Implementation simplicity	Impact on localisation performance, unstable performance, previous result required, additional equipment required

- Efficient and accurate NLOS identification with less data volume required. Currently, the AI based approaches attract lots of attention in NLOS identification, owing to the capability for precise feature comparison. Large data volume is needed to provide enough sample for precise identification. However, as aforementioned, it is difficult to gather plenty of data for comparison due to the operational environment of UAV.
- Effective NLOS mitigation algorithm with low computational complexity. Alone with the introduction of the NLOS mitigation algorithm, the computational complexity of the localisation algorithm is definitely increased which has the dramatic effect on localisation latency and operation time of UAV. The problem can be solved by additional localisation server. However, the unpredictable signal block or interference between UAV and the localisation server will cause the position lost of UAV.
- Precise localisation with low communication cost (for synchronisation-free algorithm). As aforementioned, the synchronisation-free localisation algorithms (TW-TOF, DS-TWR, SDS-TWR, etc.) successfully solved the node synchronisation problem and achieved precise localisation at the expense of communication cost. For traditional applications, the additional communication between sensor nodes can be ignored directly due to the low demand for position update rate. But for UAV applications, the position update rate or localisation latency is closely related to the stability of UAV. Thus, how to reduce the communication cost of the synchronisation-free algorithms will be the extremely important question for UAV positioning.
- Accurate relative synchronisation with low computational complexity and communication cost. In order to estimate the relative clock offset and skew, additional communication between sensor nodes and relative synchronisation algorithm are required. Thus, as discussed, the computational complexity and additional communication cost lead by relative synchronisation algorithm will be the factors influencing the localisation latency and position update rate of UAV.
- How to achieve precise anchor self-localisation with less prior information and additional equipment. Currently, the anchor self-localisation approaches still need the prior information such as some known position anchor nodes, existing geometry for operational environment or additional equipment like smart antenna array. However, these all will still restrict the application scenarios of UAV, especially in dynamic or unknown environment. Thus, the precise anchor self-localisation with less prior information and additional equipment is particularly important under current circumstance.
- Precise relative localisation of UAV swarm with low computational complexity and robust to NLOS error. As mentioned before, the relative localisation approaches for UAV swarm have already been implemented through the communication between sensor nodes on each UAV. However, NLOS error between sensor nodes and the problem of high computational complexity are never taken into account in the current approaches which run counter to the application scenario in GPS-denied environment and have the huge impact on localisation latency. Thus, precise relative localisation of UAVs which show robustness to NLOS error with low computational complexity is another burning issue in this area.

6 Conclusion

In this paper, a comprehensive analysis and overview have been presented for the RF based UAV localisation systems with different radio communication technologies under different localisation mechanisms to demonstrate the current circumstance of the RF based UAV localisation technologies in GPS-denied environment, considering the missing of survey literature in the current field. Firstly, the pros and cons of the existing RF based UAV localisation systems with different radio communication technologies (Wi-Fi, Bluetooth, Zigbee, RFID, UWB) were discussed. Later on, the classical localisation mechanisms (RSS, AOA, TOF/TOA, TDOA, Fingerprint) widely used on the RF based localisation systems and the effectiveness of each for UAV positioning in GPS-denied environment were reviewed. Thirdly, the evaluation framework to assess the system performance was established, aiming at the special demand for UAV positioning in GPS-denied environment. Similar to our work, a comprehensive evaluation framework has also been established in [15], but more attention has been given to the energy efficiency. As aforementioned, sensor nodes are able to power themselves with the on-board battery which have no impact on UAV operation time. Meanwhile, considering UAV is not a long-life system, to keep sensor nodes alive within the operation process of UAV is enough. For the UAV application, greater emphasis should be put on the localisation latency which is different from the traditional applications. With the established framework, all the RF based localisation systems with the specific localisation mechanisms are analysed to find the suitable application scenarios. According to the analysis, except the Zigbee based systems, all the other RF based localisation systems are able to be applied on UAV positioning. Within these, the Wi-Fi based systems with the RSS based localisation mechanisms are more suitable for the UAV positioning in outdoor environment. Both the Bluetooth and RFID based localisation systems are more effective for the applications on MAVs or micro-uavs in smaller indoor environment. Particularly, the UWB based system with the time-based localisation mechanisms are highlighted for UAV positioning under the consideration of the proposed evaluation framework, which can be the best option for UAV positioning with the RF based systems.

Finally, key issues and challenges for UAV positioning with the RF based system in GPS-denied environment were discussed. According to our investigation and comparison in Table 3, the previous surveys in [13–18] all presented the challenges for the existing localisation technologies. Especially for the authors in [14] and [15], a comprehensive discussion and analysis for the current challenges were provided. Nevertheless, the specific challenges for UAV positioning including Relative Localisation, Signal Block or Interference and Unreasonable Value were never considered by Zafari et al. [15]. Singh et al. [14] only considered the basic applications on UAV. Furthermore, the current challenges including drone velocity, strong multipath, NLOS and computational load were presented in [17] which focused on the UAV applications. But the detailed analysis and KPIs to evaluate the performance of each system or technology were never mentioned. Consequently, the analysis and discussion on the key issues and challenges for the specific applications on UAV positioning in our work can provide some promising directions for future research.

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Authors' Contributions

Beiya Yang conceived the work, performed the literature review, drafted the manuscript and revised it critically for important intellectual content. Erfu Yang revised the manuscript critically for important intellectual content and approved the version to be published. All authors reviewed and approved the final manuscript.

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