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Abstract

With Unmanned Aircraft System (UAS) being developed and deployed for an increasing number of applications, it is essential to meet demanding separation assurance and navigation performance requirements, especially considering the current evolutions of the UAS Traffic Management (UTM) research framework. However, in dense urban environments characterized by tall buildings and complex man-made structures, Global Navigation Satellite System (GNSS) is prone to data degradations or complete loss of signal due to multipath effects, interference or antenna obscuration. Furthermore, there is always a risk of jamming and spoofing of GNSS signals, with low cost civilian GNSS receivers being more vulnerable to a spoof attack. Therefore, a number of Signals of Opportunity (SoOP) techniques are being explored to improve the navigation performance when UAS are employed in urban canyons. Electromagnetic signals found in urban environments including analogue/digital radio, analogue/digital television, Wi-Fi, Global System for Mobile Communications (GSM) and Code Division Multiple Access (CDMA) based signals are considered to model the system performance parameters. Implementation methods for exploiting SoOP such as Angle of Arrival (AOA), Time of Arrival (TOA), Received Signal Strength (RSS) and Time Difference of Arrival (TDOA) are introduced and compared. Integration of SoOP techniques in novel low-cost Navigation and Guidance Systems (NGS) is also investigated. As SoOP are not natively intended to be used for navigation purposes, no single source of SoOP for navigation can work in all environments and hence a SoOP source has to be selected based on specific requirements in the considered urban environment. Constraints of power and weight on the Unmanned Aerial Vehicle (UAV) besides hardware and software costs are also factors that are considered when selecting appropriate SoOP signal sources. Therefore, there is a clear opportunity for considerable savings in both infrastructure and energy costs by providing a low-cost and low-volume integrated NGS solution for trusted autonomous aerial operations.

Keywords: Signals of Opportunity; UAV; Navigation and Guidance systems; urban canyons
1. Introduction

Unmanned Aerial Vehicles (UAV) are increasingly being used in scenarios considered “dull, dirty or dangerous” for manned aircraft. This could, in many situations, require the UAV to navigate thorough urban landscapes, consisting of tall buildings and complex man-made structures. On-board UAV navigation primarily relies on Inertial Navigation Systems (INS), in conjunction with Global Navigation Satellite Systems (GNSS) receivers, though research is increasingly supporting the integration of Vision-Based Navigation (VBN) sensors and other low cost sensors like acoustic, magnetic and GNSS for Attitude Determination (GAD). In urban environments, GNSS signals are prone to data degradations that could also result in the complete loss of data in some situations [1-4]. Owing to this, there has been an increasing research focus on utilizing SoOP for NGS.

Various signal sources have been identified for UAV navigation and guidance applications in dense urban environments. Analogue/digital radio, analogue/digital television, Wi-Fi and GSM/CDMA signals have shown potential for being used as SoOP for navigation [5, 9-14]. The implementation methods for using signals of opportunity are Angle of Arrival (AOA), Time of Arrival (TOA), Received Signal Strength (RSS) and Time Difference of Arrival (TDOA) [5, 12].

This research focuses on adopting various SoOP signals available in the urban environments and the ways to utilize them. All potential SoOP signal sources are described with the implementation method employed to get the navigation data from the signal. The advantages and limitations of using a particular SoOP signal source for navigation and guidance are also discussed. After explaining the various SoOP implementation methods and their use for a particular signal, the paper sums up the findings and lays down the path for future research.

2. SoOP sources

2.1. Television signals

Television signals are a good candidate as SoOP for navigation. Digital terrestrial service works with analogue TV transmissions allocated on VHF (Very High Frequency) and UHF (Ultra High Frequency) part of the frequency system. However, with more viewers shifting to digital TV, the usage of analogue TV has greatly declined. The signal structure standards of digital television used globally are Advanced Television Systems Committee (ATSC) in North America, Digital Video Broadcasting (DVB) in Europe, Australia and large parts of Asia, Integrated Services Digital Broadcasting-Terrestrial (ISDB-T) in Japan and Digital Terrestrial Multimedia Broadcast (DTMB) in China [13-16]. GNSS can be suitably complemented by TV signals based localization system in an urban environment where GNSS tends to fail. The broad coverage and high transmission power of TV signals makes it possible to achieve low Horizontal Dilution of Precision (HDOP) for navigation [17]. The TV signals have a much higher bandwidth of 6-8 MHz, which helps mitigate effects of multipath [17, 18]. Low and diverse frequencies and high power of TV signals make them ideal for indoor and urban reception [19].

However, transmitted TV signals lack inclusion of transmission time information or time stamps. Transmitter clocks in TV transmitters are quite unstable with large drifts in oscillators causing large frequency offsets [10, 19]. To overcome the errors in transmission time, a network of regional monitor stations has been suggested, which can broadcast the corrected timing information for each TV station [19]. Setting up monitor stations will involve a huge expenditure. So, using TDOA, with two receivers, seems more practical for TV signals. Since both the receivers are proposed to be fitted on the UAV, the requirement of a large bandwidth between the two can be comfortably met.

2.2. Audio signals

Studies have been conducted on using both analogue (FM and AM) and digital audio signals for navigation [9, 20, 21]. The standards for digital audio are iBiquity in United States, Digital Audio Broadcasting (DAB) in Europe and Australia, and ISDB-T in Japan [22]. The advantage of using audio signals for navigation are low cost of hardware, low power requirements at the receiver side, high transmission power, good reception in urban areas (both indoor and outdoor) and availability of large number of transmitters.
But, there are certain challenges in using audio signals for navigation. FM signals do not carry any timing information and FM transmitters are unsynchronized in time, frequency and phase [23]. Also, FM signals are degraded by effects of multipath and non-line-of-sight (NLOS) signals. DAB signals, though, have certain characteristics such as the synchronization channel, which facilitates localization. However, there are still certain issues like timing delay between different Single Frequency Networks (SFN), height of transmitters and the Dilution of Precision (DOP) values based on the exact location of transmitters and the geometry they provide [23]. A significant number of FM transmitters present in an urban environment makes their utilization as a SoOP for navigation feasible. In the presence of a reference receiver, TOA, TDOA and AOA techniques can be used for localization. Although, utilization of RSS technique does not require additional hardware, the empirical approach is prone to errors and fingerprinting, besides being labor intensive, requires regular updating of data maps due to changing conditions in the environment [21].

2.3. Wi-Fi signals

With various mobile devices supporting Wi-Fi, Wireless Local Area Networks (WLAN) are increasingly becoming popular in households as well as commercial establishments. Wi-Fi is any WLAN based on the Institute of Electrical and Electronics Engineers' (IEEE) 802.11 standards. Wi-Fi network can be easily installed and does not require a prior spectrum license. Efforts have been made to utilize Wi-Fi signals in localization techniques. Companies like Google and Skyhook Wireless utilize their database of known locations of Wi-Fi access points along with GNSS and cell tower data to develop a localization system. Although Wi-Fi signals are abundantly available in an urban environment, they have certain drawbacks which can hinder their utilization as a SoOP. Wi-Fi signals have a short range, so are not suitable for outdoor localization and are prone to interference from electronic devices. With increasing number of Wireless Access Points (WAP) available in an urban environment, Wi-Fi provides sufficient coverage and enough transmitters for localization. The most common technique used for Wi-Fi based indoor localization is RSS using fingerprinting [24], which is time consuming and requires continuous updates. Using other localization techniques for Wi-Fi signals will require additional hardware and software, which will eventually increase the cost of the system.

GSM signals are default global standard for mobile communications, operating in over 218 countries [23]. GSM operates in various bands globally, with 900 MHz and 1.8 GHz bands in Europe, 850 MHz and 1.9 GHz bands in the US and 850 MHz band in Australia and Canada. GSM signals are already being used in location estimation of a mobile device, owing to Federal Communications Commissions' (FCC) demand from service providers to generate Position Location (PL) estimates for Enhanced-911 (E-911) emergency calls [25]. GSM signals have the advantage of large number of cellular towers, especially in densely populated urban areas, and lack of interference from nearby devices due to licensed spectrum. With multiple operators, sufficient number of cellular towers is available, leading to a good geometry and a lower DOP.

However, GSM based localization is greatly affected by multipath and NLOS, especially in urban or indoor environments [23]. Owing to low power and narrow bandwidth of GSM signals, the cell-identity based position estimation is degraded to a few hundred metres, which is not acceptable for navigation purposes [26]. GSM base stations are not synchronized. So, position calculation by TOA or AOA approach can be a challenge. RSS with fingerprinting approach can be applied, but creating a data map is labor intensive and time consuming. TDOA technique, with a hardware capability to measure time of propagation of known transmitted signals with local replica generated inside the receiver, can be utilized. GSM signals can also support the GNSS, as in Assisted GPS, by reducing the time-to-fix and increasing the sensitivity of GNSS receivers [27].

3. SoOP localization techniques

3.1. Angle of Arrival

AOA is defined as the angle between the propagation direction of an incident wave and a reference direction, called orientation. Orientation is a fixed direction represented in degrees in a clockwise direction from the North. AOA is absolute when the orientation is 0° or pointing to the North, otherwise is relative. AOA measurements can
be made by using an antenna array on each receiver node [28]. AOA measurements can also be made using an antenna triad. Comparison of RSS to the three antennas is used to compute AOA [5]. Localization in AOA can be solved by triangulation. Triangulation is similar to trilateration, used in GPS, except the receiver knows the angles of the received signals from transmitters, instead of distance measurements of transmitters from receivers in trilateration [29]. The triangulation problem in AOA can be reduced to trilateration by some transformations. In a Two Dimensional (2-D) case, if a receiver R measures the angle to a pair of transmitters T1 and T2, it can be inferred that the position of R is somewhere on the circle determined by the measured angle and the position of the two transmitters, as illustrated in Fig. 1.

![Fig. 1. Deducing distances from angles.](image)

Hence, the transformed triangulation problem involves x, y, x0, y0 and radius of the circle as the distance. Thus, a triangulation problem of size n is reduced to a trilateration problem of size. Given (xi, yi), the coordinates of the ith transmitter and di, the distance of the ith transmitter to the receiver, the equation of the non-linear system is

\[(x-x_i)^2 + (y-y_i)^2 = d_i^2 \quad i = 1, \ldots, n\]  

(1)

Linearising the equation by subtracting one equation from the rest

\[2x(x_i-x_j) + 2y(y_i-y_j) = d_i^2 - d_j^2 + x_i^2 - x_j^2 + y_i^2 - y_j^2 \quad i = 2, \ldots, n\]  

(2)

The equations can be solved by least squares approximation (LSA) for an overdetermined system [30]. Instead of using three antennas, three or more transmitters, with prior knowledge of transmitter power and path loss model, can be used to compute the distance of receiver from the transmitter based on RSS [31]. However, angular measurements are more prone to errors than TDOA measurements [32] and the accuracy of final position estimate reduces rapidly as the receivers move away from the source [12]. Antenna array installation on UAV can also be a challenge in terms of payload limitations.

3.2. Time of Arrival

In 2-D, TOA determines the position of the receiver based on the intersection of three or more circles whose radii being the distance of the respective transmitter from the receiver [33]. Imperfect readings lead to a region of uncertainty in receiver location, as illustrated in Fig. 2 [30]. Transmit time and transmitter ephemeris data needs to be transmitted [5] or the receiver needs to have a priori knowledge of the transmitter locations. But, clock synchronization of transmitters and receiver is still a challenge. The coordinates of the receiver can be calculated using trilateration, by solving the system of nonlinear equations by LSA for an overdetermined system. In three dimensional cases, the receiver coordinates are calculated from intersection of spheres, with the transmitters located at their respective centers. A general expression for range measurement \(R_k^i(t_k)\) is given by:

\[R_k^i(t_k) = p_k^i(t_{r,k}) - (dt_k - dt^i)v + P_{k,x}^i(t_k) + P_{k,y}^i(t_k) + P_{k,z}^i(t_k) + d_{k,x}^i(t_k) + d_{k,y}^i(t_k) + d_{k,z}^i(t_k) + \epsilon_i\]  

(3)
where:
\( \rho_{k}(t_{r}, t_{k}) \) = geometric distance;
\( P_{k}(t_{r}) \) = propagation delay in air (standard conditions);
\( d_{kT}(t_{k}) \) = receiver clock error;
\( d_{kT}(t_{r}) \) = transmitter clock error;
\( d_{kT}(t_{r}) \) = multipath error;
\( \varepsilon \) = random measurement noise.

Fig. 2. TOA in 2-D case.

3.3. Received Signal Strength

RSS can be an economical localisation method since it does not require additional hardware and the receivers are relatively cheap. RSS has been investigated on Wi-Fi and Bluetooth signals. RSS can be measured either by range-based approach, signal fingerprinting or range-free approach. Range-based approach performs localisation by estimating the distance of the receiver to the Wireless Access Point (WAP), converting RSS to a metric value and using known locations of WAPs. The distances are compared in order to localise the receiver. For signal fingerprinting, a model of RSS, built using a data map for a set of known locations is used to compare all measured RSS values. The position of receiver is calculated based on the best match via an empirical position estimation algorithm such as the nearest neighbour algorithm. Path loss modelling, as shown in equation 3, can be used to calculate the distance between the transmitter and receiver.

\[
RSSI = 10 \alpha \log(d)
\]  

\[
d = 10^{\frac{RSSI - RSSI_{\text{calibration}}}{10 \alpha}} + d_{\text{calibration}}
\]  

where \( d \) is the distance between transmitter and receiver, \( RSSI \) is the RSS indicator, \( RSSI_{\text{calibration}} \) is RSSI offset, \( \alpha \) is the path loss gradient of the environment and \( d_{\text{calibration}} \) is the distance offset. Range-free approach employs techniques such as Gaussian process. Although, RSS techniques do not require extensive hardware on the receiver side, which is an advantage while using this technique as a SoOP in UAV, there are certain limiting factors. Constructing data maps for fingerprinting localisation can be time consuming and expensive. Path loss models have a large margin of error and are unpredictable. RSS-based localisation gets adversely affected in indoor environments by electric devices and multipath interferences, like walls, ceilings and even metal objects. Performance in outdoor environments too gets affected by multipath obstructions. RSS requires knowledge of transmitted power and path loss component. Also, the assumptions that the transmitter is isotropic and there is no multipath or shadowing generally do not hold true.
3.4. Time Difference of Arrival

TDOA or hyperbolic positioning is used in E911 and was adopted in long range navigation (LORAN) system till it was discontinued [37]. For TDOA, a pair of passive receivers are used which measure the relative TOA of transmitted signals [5, 10, 12]. The TDOA is calculated, which, assuming no noise, is a hyperbola (Fig. 3).

![TDOA calculation](image)

Fig. 3. TDOA calculation.

One of the receivers is designated as a reference, which pairs with other receivers in calculation of transmitter location. So, for n available receivers, n-1 pairs can be formed and emitter position is calculated from n-1 hyperbolae. Usually, it requires n+1 receivers to calculate transmitter location, n being the dimension of the coordinates. So, for a 2-D case, three receivers are needed to calculate the location of the transmitter provided the three receivers are not collinear [38]. SoOP based TDOA is an absolute navigation technique and requires less payload, does not require synchronized transmitter and receiver clocks, knowledge of transmit time or location of transmitter. However, TDOA computations require sharing of data between receivers, which in turn increases bandwidth and power demands [12].

4. Conclusion

This paper investigated the use of SoOP for UAV navigation in urban environments, where high levels of accuracy are required and GNSS has very limited availability. Various sources of SoOP were investigated for their potential feasibility in integrating with state-of-the-art NGS solutions. SoOP can be used for GNSS Avionics Based Integrity Augmentation (ABIA) systems, by addressing the challenges of masking and multipath modeling typical of an urban environment [1-4]. New integrity flag thresholds would be required to account for the back-up functionalities provided by SoOP. Several SoOP sources already exist and their exploitation does not require additional infrastructure (for transmission) or extensive redesign of existing receiver radiofrequency front-ends and signal processing, thus saving on costs and energy. Future work will involve performing hardware-in-the-loop simulations for a number of proposed NGS solutions, which will integrate SoOP with GNSS, INS, acoustic sensors, GAD and VBN. This will enable further improvements in the NGS architectures and support flight tests in controlled urban environments.

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