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## Survey of Relative Navigation Methods for Multi-Agent Unmanned Aerial Vehicle Systems

### **Abstract**

*Multi-agent Unmanned Aerial Vehicle (UAV) systems require stable and high-precision navigation. The existing navigation solutions, such as global navigation satellite systems (GNSS) and inertial navigation systems, may perform inefficiently in some application scenarios. The relative navigation methods can help solve this problem. Relative navigation enables UAVs to precisely estimate their positions relative to each other, as opposed to absolute navigation, which calculates the UAVs' position relative to the Earth. Despite the abundance of relative navigation articles, there are no systematic reviews of relative navigation methods. Additionally, various articles on relative navigation use a variety of terms for comparable concepts, which makes it more difficult to understand the subject. Therefore, this review comprehensively studies systematizes relative navigation methods, and analyzes their strengths and weaknesses. We categorize relative navigation methods appropriate for multi-UAV systems, compare them, and make conclusions based on our findings. The relative navigation methods discussed in this review include differential GNSS, radio-frequency-based, visual, and their combinations. We evaluate the achievable accuracy and range for each type of method according to related studies. We also describe the limitations and vulnerabilities of each method. As a result, we outline relative navigation's primary capabilities and assess its condition now.*

**Keywords:** cooperative navigation, relative position estimation, navigation fusion, relative positioning, relative attitude estimation, collaborative navigation, network localization

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## Обзор методов относительной навигации в группах беспилотных летательных аппаратов

*Групповое применение беспилотных летательных аппаратов (БПЛА) требует стабильной и высокоточной навигации. Существующие навигационные решения, такие как глобальные навигационные спутниковые системы (ГНСС) и инерциальные навигационные системы, могут работать неэффективно в некоторых сценариях применения. Эту проблему можно решить с помощью методов относительной навигации. В отличие от абсолютной навигации, которая оценивает положение БПЛА относительно Земли, относительная навигация позволяет точно оценить положение БПЛА относительно друг друга. Несмотря на большое число публикаций по относительной навигации, обзоры ме-*

тодов относительной навигации, систематизирующие существующие исследования, практически не встречаются. Кроме того, в различных статьях об относительной навигации используется широкий спектр терминов для схожих понятий, что усложняет изучение темы. Поэтому в данной статье подробно рассматриваются и систематизируются методы относительной навигации и анализируются их возможности и ограничения. На основании результатов обзора предлагается классификация методов относительной навигации, подходящих для групп БПЛА, и представляются результаты их сравнительного анализа. В статье рассмотрены дифференциальные ГНСС, радиочастотные и визуальные методы относительной навигации, а также их комбинации. Для каждого типа метода оцениваются достижимая точность и дальность действия в соответствии с соответствующими исследованиями. Также представляются ограничения и недостатки каждого метода. В результате сформулированы основные возможности относительной навигации и оценено ее текущее состояние.

**Ключевые слова:** совместная навигация, применение БПЛА, группы БПЛА, оценка относительного положения, относительная локализация, комплексирование методов навигации

## Introduction

Unmanned Aerial Vehicle (UAV) systems have numerous applications in both civil and military contexts. Up till now, various multi-UAV systems have been widely discussed as such systems have more advantages than single-UAV systems. The advantages are discussed in detail in [1], and the following are just the most salient ones:

- *Fault tolerance:* if one or more UAVs fail, the remaining UAVs complete the task using appropriate algorithms.
- *Time efficiency:* task parallelization can greatly shorten the mission's operational time.
- *Simultaneous actions:* in contrast to a single UAV, a multi-UAV system can complete tasks in several geographic places at the same precise time.
- *Cost:* reduced operational time results in reduced energy consumption.

Despite their substantial capacity, multi-UAV systems are still uncommon in daily life. "Drone show" [2, 3] and visual inspection of aircraft [4] are two examples of the existing practical applications.

Unsolved problems hindering the widespread use of multi-UAV systems include legal and technical

challenges. One of the primary technical problems is related to the stable and high-precision navigation of UAVs. Commonly, it is solved using global navigation satellite systems (GNSS), usually with real-time kinematic (RTK) techniques, and inertial navigation systems (INS). However, due to INS error propagation and restricted satellite visibility, this solution may occasionally be compromised, which makes it necessary to find additional solutions to complement the ones already in place.

One such solution is relative navigation (RelNav). Absolute navigation involves estimating an object position relative to a global coordinate system, whereas RelNav concentrates on precisely estimating object positions relative to one another. In some cases, RelNav data can be used to improve the absolute navigation accuracy of each object. This approach is called cooperative navigation (CoopNav) [5].

The RelNav research direction is actively developing, which is confirmed by numerous studies published over the last few years (Fig. 1) [6]. Therefore, there has been no conventional terminology for RelNav yet. The authors use various similar terms for RelNav and CoopNav: relative positioning, relative localization, relative attitude estima-

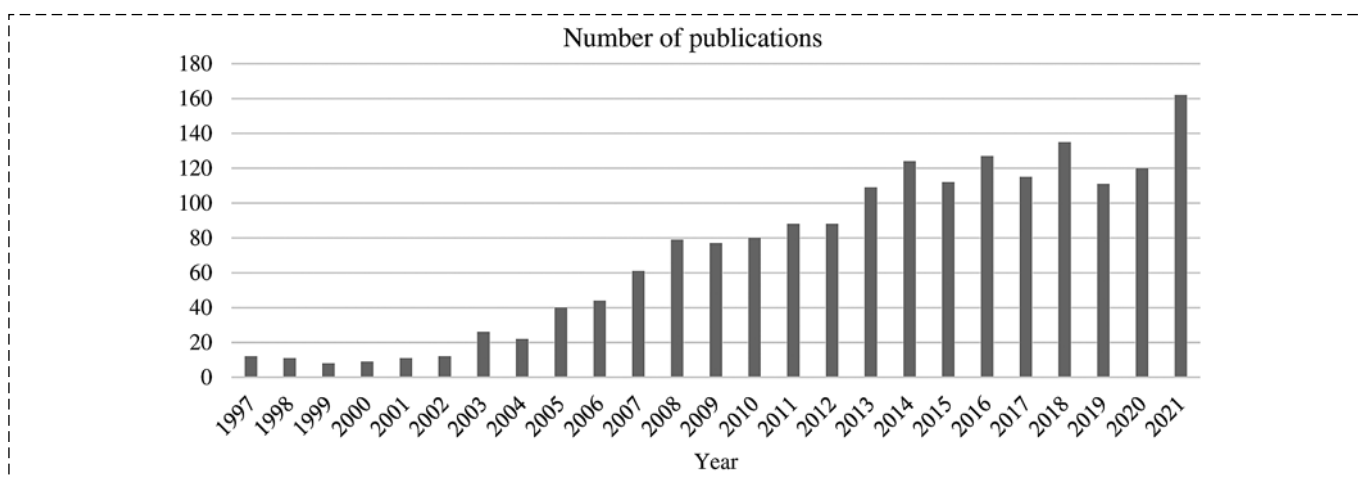


Fig. 1. Publication statistics for the last 25 years found by the request "relative navigation" OR "cooperative navigation" in the science citation database "Scopus"

tion, collaborative navigation, cooperative positioning, network localization, etc. In this review, we will use the terms defined above.

RelNav can be applied not only to multi-UAV systems but also to other robotic systems, cars, satellites, and the internet of things. These applications are not covered in this review as, on the one hand, UAVs have the greatest practical demand and, on the other hand, wide access to UAVs allows for theoretical and experimental investigation.

Despite the vast quantity of RelNav studies, there are hardly any systematic reviews of RelNav methods. The majority of current reviews focus on RelNav methods for satellites that can be applicable to UAVs [7–9]. Few reviews of UAV RelNav mostly emphasize visual navigation methods though they ignore differential and radio methods [10]. At the same time, surveys on multi-UAV problems, including navigation problems, also do not mention RelNav and CoopNav methods [11].

This review's objectives include systematizing RelNav methods used in multi-UAV systems and examining their capabilities, achievable characteristics, and limitations. The review is intended for multi-UAV system researchers who need to improve the precision and stability of navigation. It may also be helpful for relative navigation method researchers.

The review is organized as follows: Section 2 describes the proposed RelNav classification. Sections 3–10 describe different RelNav methods in detail. Finally, Section 11 presents the analysis of the capabilities and limitations of RelNav methods.

### Method classification

In this review, we classified RelNav methods according to the used sensors as this feature largely determines the capabilities and limitations of the methods. The proposed classification is summarized in Fig. 2 and fully presented in the following sections.

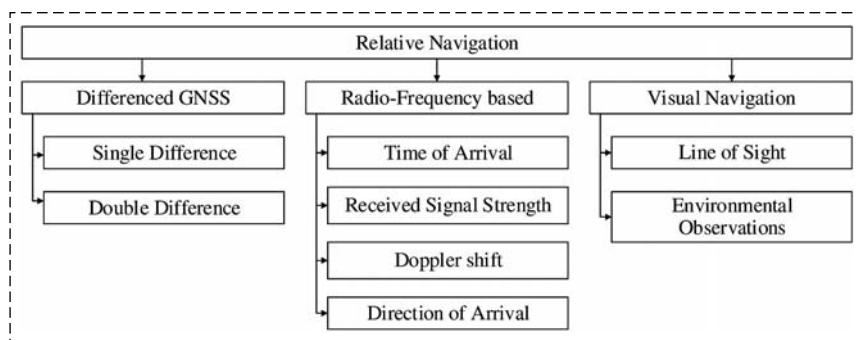


Fig. 2. Method classification

### Differenced methods

The most common types of GNSS observations are a pseudorange and a carrier phase [12]:

$$\rho_m^i = r_m^i + c(dt^i - dt_m) + \iota_{\rho m} + \tau_{\rho m} + \varepsilon_{\rho m};$$

$$\varphi_m^i = \lambda^{-1}[r_m^i + c(dt^i - dt_m)] - N_m^i + \iota_{\varphi m} + \tau_{\varphi m} + \varepsilon_{\varphi m},$$

where  $\rho_m^i, \varphi_m^i$  are the pseudorange and carrier phase observations; subscript  $m$  and superscript  $i$  refer to receiver  $m$  and satellite  $i$ , respectively;  $r_m^i$  is the distance between the satellite and the receiver;  $c$  is the speed of light and  $\lambda$  is the wavelength;  $dt^i$  and  $dt_m$  are the satellite and the receiver clock offsets;  $N_m^i$  is the carrier phase ambiguity;  $\iota$  and  $\tau$  are the ionosphere and troposphere errors, and  $\varepsilon$  are the receiver-dependent errors.

These measurements suffer from a variety of errors. Fortunately, most of the error components are eliminated by linearly combining the matched measurements from two closely spaced receivers. This fact is widely used in DGNSS methods.

The most common DGNSS method is referred to as Single Difference (SD), which helps to reduce ionosphere and troposphere errors and satellite clock offsets. A SD observation for receivers  $m$  and  $k$ :

$$\rho_{mk}^i = \rho_k^i - \rho_m^i = r_{mk}^i + cdt_{mk} + \Delta\iota_{\rho} + \Delta\tau_{\rho} + \varepsilon_{\rho mk};$$

$$\rho_{mk}^i \approx r_{mk}^i + cdt_{mk} + \varepsilon_{\rho mk};$$

$$\varphi_{mk}^i = \varphi_k^i - \varphi_m^i = \lambda^{-1}[r_{mk}^i + cdt_{mk}] - N_{mk}^i + \Delta\iota_{\varphi} + \Delta\tau_{\varphi} + \varepsilon_{\varphi mk};$$

$$\varphi_{mk}^i \approx \lambda^{-1}[r_{mk}^i + cdt_{mk}] - N_{mk}^i + \varepsilon_{\varphi mk},$$

where  $r_{mk}^i = r_k^i - r_m^i$ ,  $dt_{mk} = dt_k - dt_m$ ,  $\varepsilon_{mk} = \varepsilon_k + \varepsilon_m$ ,  $N_{mk}^i = N_k^i - N_m^i$ ,  $\Delta\iota = \iota_k - \iota_m \approx 0$ , and  $\Delta\tau = \tau_k - \tau_m \approx 0$  for closely spaced receivers.

The relation between SD measurements and receivers' relative positions is shown in Fig. 3 and given by a system of linear equations:

$$r_{mk}^i = \mathbf{b}_{mk} \mathbf{u}_m^i,$$

where  $\mathbf{b}_{mk}$  is the baseline vector for receivers  $m$  and  $k$ ;  $\mathbf{u}_m^i$  is the unit line-of-sight (LoS) vector for receiver  $m$  and satellite  $i$ , and  $\mathbf{u}_m^i = \mathbf{u}_k^i$  is supposed.

Another method called Double Difference (DD) can eliminate the receiver clock error component in SD. A DD observation is formed by differencing two SD observations:

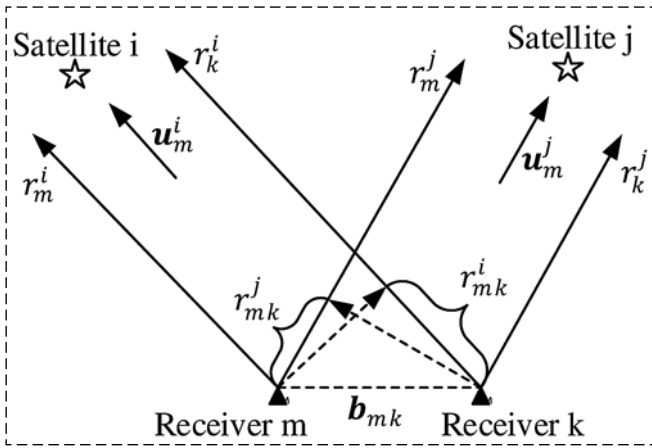


Fig. 3. Single difference method [16]

$$\begin{aligned} \rho_{mk}^{ij} &= \rho_{mk}^j - \rho_{mk}^i = r_{mk}^{ij} + \Delta t_\rho + \Delta \tau_\rho + \varepsilon_{\rho mk}; \\ \rho_{mk}^{ij} &\approx r_{mk}^{ij} + \varepsilon_{\rho mk}; \\ \varphi_{mk}^{ij} &= \varphi_{mk}^j - \varphi_{mk}^i = \\ &= \lambda^{-1} r_{mk}^{ij} - N_{mk}^{ij} + \Delta t_\varphi + \Delta \tau_\varphi + \varepsilon_{\varphi mk}; \\ \varphi_{mk}^{ij} &\approx \lambda^{-1} r_{mk}^{ij} - N_{mk}^{ij} + \varepsilon_{\varphi mk}, \end{aligned}$$

where  $r_{mk}^{ij} = r_{mk}^j - r_{mk}^i$ ,  $N_{mk}^{ij} = N_{mk}^j - N_{mk}^i$ .

The system of linear equations for DD is:

$$r_{mk}^{ij} = b_{mk} (\mathbf{u}_m^j - \mathbf{u}_m^i).$$

As a result, the receiver clock offset is eliminated and the DD accuracy is higher than SD. However, the DD method causes additional computational complexity.

One of the earliest studies of RelNav [13] describes a method based on SD pseudorange and INS observation fusion in leader-follower multi-UAV system. Leader GNSS and IMU measurements are transmitted to followers and fused to a relative position with a federated Kalman-like filter.

Subsequent studies on the DGNSS/INS approach relate to new filter and fusion methods. For example, in [14], the authors presented an adaptive filter. The adaptive carrier-smoothed-code (CSC) algorithm estimates relative position and position covariance from SD observations. Afterward, the CSC result and INS measurements are fused in an adaptive Kalman filter for relative state estimation.

The leader-follower architecture of the described methods is sensitive to individual aircraft failures. Therefore, another direction for research is in distributed relative navigation. The authors of [15] introduces a full parallel distributed structure. Each aircraft acts as a fusion center and calculates its relative position with the other aircraft in the formation. The filtering algorithm has a two-stage struc-

ture. In the local filter, GPS observations are used to correct INS long-term errors. In the relative state filter, the DGNSS data and the local filter results are used to estimate the error in relative position.

Like all GNSS methods, the DGNSS methods are corrupted by signal blockage, heavy multipath interference, and Non-Line-of-Sight (NLoS) reception in urban environments. To solve this problem, the paper [16] proposes integrity monitoring of a DD relative navigation system. The comparison of spatially distributed GNSS observations enables the detection and exclusion of GNSS signal faults. Besides, the method is effective for collision avoidance due to evaluation of relative position errors.

The *accuracy* of DGNSS relative navigation is comparable to RTK through similar principles and about 0.1 m.

The DGNSS *range* is not strictly limited, but as the distance increases, the accuracy declines.

The DGNSS is *vulnerable* to jamming, spoofing, multipath, and NLoS and depends on the availability of GNSS satellites.

### Time of Arrival

Another relative navigation approach involves using peer-to-peer radio-frequency (RF) communication to obtain additional information. One of the most common RF-based methods is time of arrival (ToA) ranging.

In the ToA method, the distance between the radios measured by radio propagation time:

$$b_{m,k} = |\mathbf{b}_{mk}| = c \Delta t_{m,k},$$

where  $b_{m,k}$  is the distance between the radios  $m$  and  $k$ ;  $c$  is the speed of light;  $\Delta t_{m,k}$  is the time interval between emitting and receiving a signal.

The ToA accuracy depends on the autocorrelation width of the signal, and, consequently, on its bandwidth. Therefore, the ToA method is usually implemented using ultra-wideband (UWB) modules. For relative navigation, range information is fused with other sensors' data.

In one of the earliest studies of ToA in RelNav [17], the authors used radio ranging with "Time Domain's P-410 UWB" and DGNSS/INS data. The proposed filter has three stages. The first stage is a local GNSS/INS filter. The second stage is a relative position filter fusing range information, DD observations, and first-stage results. Finally, ambiguities are resolved using the Least-squares AMBIGUITY Decorrelation Adjustment (LAMBDA) method [18] and relative position is corrected in the third stage.

One of the goals of ToA and DGNSS fusion is to eliminate the DGNSS disadvantages. Several works are dedicated to GNSS fault detection and exclusion (FDE) using additional ToA observations [19–21]. In [19], the authors applied the residual-based snapshot method [22]; whereas the paper [20] proposes a combination of the Kalman filter-based receiver autonomous integrity monitoring [23] and Huber’s M-estimation based Kalman filter [24]. Another paper [21] proposes an FDE method based on Kullback–Leibler divergence (KLD) between a prior and posterior distributions. According to the findings, the KLD-based method outperforms the traditional  $\chi^2$ -based method in terms of robustness.

Overcoming interference inherent in GNSS signals allows DGNSS/INS/ToA methods to improve the accuracy of absolute navigation. This approach is known as cooperative navigation. The authors of [25] examine cooperative navigation for multiple vehicles (cars) in urban environments. The authors achieved resistant absolute position estimation to multipath and NLoS by adapting the sum-product algorithm over wireless networks (SPAWN) [26] and the hybrid cooperative extended Kalman filter (hcEKF) [27].

Subsequent several studies [5, 28, 29] on DGNSS/INS/ToA CoopNav propose and analyze different filtration methods. These papers consider cars and UAVs as objects of navigation.

The ToA method, like all RF methods, is susceptible to jamming.

The article [30] that addresses this issue considers a situation with partially denied navigation signals (e.g., ToA jammers for some UAVs and GNSS jammers for others). The authors proposed a modified sigma-point belief propagation algorithm (SPBP) [31] —SPBP of random packet loss (SPBP-RFL), which uses the observations of several UAVs at the current and previous steps.

Another disadvantage of ToA methods is requirement of peer-to-peer LoS signal propagation. The NLoS error distribution significantly differs from the Gaussian distribution, in particular, by heavy tails [32]. Therefore, NLoS RelNav with ToA methods requires solutions other than the traditional Kalman filter. As a solution, the paper [32] proposes the Generalized Maximum Correntropy Criterion Kalman Filter.

According to the studies, the *accuracy* of DGNSS/INS/ToA methods reaches 0.01 m.

Due to the fact that most commercial UWB modules operate at high frequencies (3–15 GHz), the *range* of ToA methods usually does not exceed 300 m [33, 34].

The ToA is *vulnerable* to jamming, multipath, and NLoS and requires wide band.

### Received Signal Strength

This method is based on the received signal strength (RSS) measurements and involves peer-to-peer ranging by the signal-power attenuation at the receiver. Attenuation under idealized conditions is described by the Friis transmission equation [35]:

$$\frac{P_r}{P_t} = G_t G_r \left( \frac{\lambda}{4\pi b_{t,r}} \right)^2,$$

where  $P_r$  and  $P_t$  are the powers at a receiver and a transceiver, respectively;  $G_t$  and  $G_r$  are the antenna gains;  $\lambda$  is the wavelength and  $b_{t,r}$  is the distance between a receiver and a transceiver.

In practice, the accuracy of the RSS method depends on the noise at the receiver, multipath and NLoS, antenna pattern inhomogeneity, and atmospheric distortion. Therefore, most of the work improves the signal-power estimation accuracy.

The application of the RSS method in RelNav is similar to the ToA method. The work [36] considers the problem of relative navigation in a GNSS-denied environment. The authors introduced an antenna gain analyzer that uses a predetermined antenna pattern and INS/magnetometer/barometer observations. To estimate relative position, the authors implemented an Alan-variance-based extended colored Kalman filter.

According to the studies, the *accuracy* of the RSS method is about 5 m and lower than that of the ToA method. However, it does not require additional equipment and can work with conventional communication systems that UAVs already have.

The estimate of the RSSI method range is not given.

The RSS is *vulnerable* to jamming, multipath, and NLoS.

### Doppler shift

Another RelNav RF-method estimates range-rate by measuring the Doppler signal-frequency shift. The related dependence can be expressed as:

$$\frac{db_{t,r}}{dt} = b_{t,r} \dot{b}_{t,r} = -\frac{\Delta f_r c}{f_0},$$

where  $b_{t,r}$  is the distance between a receiver and a transceiver;  $c$  is the speed of light;  $f_0$  is the carrier frequency, and  $\Delta f_r$  is the Doppler shift.

The paper [37] considers the use of Dedicated Short-Range Communications (DSRC, IEEE

802.11p) to range-rate through the Carrier Frequency Offset (CFO) [38]. The proposed method fuses DSRC-Doppler, DGNSS, and INS measurements with an extended Kalman filter to obtain relative position.

The authors of [39] propose a DGNSS/INS/ToA/DSRC-Doppler cascade method with float and fixed steps. The float step provides the float solutions and float SD ambiguities. Afterward, the SD ambiguities are fed into the LAMBDA method to estimate the integer ambiguities. Finally, a fixed filter estimates the fixed relative position if possible.

According to the studies, the *accuracy* of DGNSS/INS/DSRC-Doppler methods reaches 0.05 m.

The *range* of DSRC-Doppler methods is 1000 m, according to the IEEE 802.11p standard.

The DSRC-Doppler is *vulnerable* to jamming, multipath, and NLoS.

### Direction of Arrival

We refer to all RF-methods that provide angle measurements with a set of antennas as Direction of Arrival (DoA).

The paper [40] discusses the relative navigation (on a plane) of cars with placing UWB modules on the cars' roofs. The scheme is shown in Fig. 4. Three UWB modules are installed on the roof of each car, denoted as  $P_{1,1}$ ,  $P_{1,2}$ ,  $P_{1,3}$  and  $P_{2,1}$ ,  $P_{2,2}$ ,

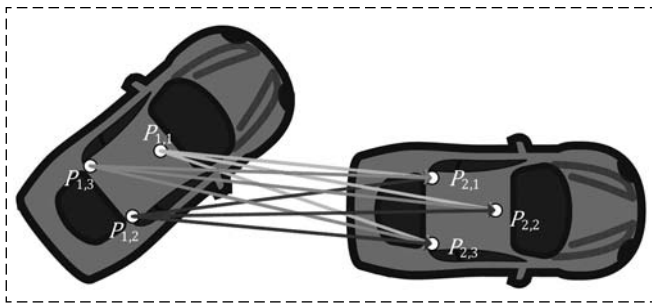


Fig. 4. Trilateration method in [40]

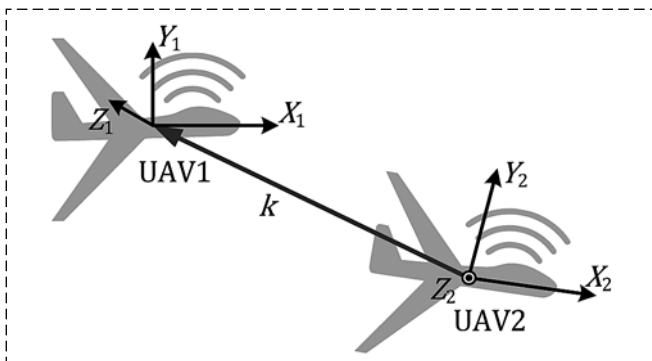


Fig. 5. DoA scheme method in [41]

$P_{2,3}$ . The relative position is calculated using nine range measurements denoted by colored lines. The authors use the multilateration method, with the Levenberg—Marquardt algorithm, and dead reckoning (INS and wheel odometry). With minor modifications, this method can also be applied to UAVs.

In [41], the authors described a method to determine all relative rotational degrees-of-freedom (DoFs) between two UAVs using a radio engineering approach, without the need of any non-RF sensors, such as INS or GNSS receivers. In Fig. 5  $X_1$ ,  $Y_1$ ,  $Z_1$ , and  $X_2$ ,  $Y_2$ ,  $Z_2$  are the local frames for UAV1 and UAV2;  $k$  is the LoS vector between the vehicles. All rotational DoF in a two-device system can be described by the vector  $[\varphi_1, \theta_1, \varphi_2, \theta_2, \alpha]$ , where  $\varphi_i, \theta_i$  are the spherical azimuth and the elevation angles of the vector  $k$  in the local frame of UAV $_i$ ;  $\alpha$  is the angle of rotation about the vector  $k$ . The proposed method uses the direction-finding techniques for multiple-input multiple-output (MIMO) channels to estimate  $\varphi_i, \theta_i$ . Then the angle  $\alpha$  is estimated using a polarimetric observation. The authors used the 6 MIMO antennas located on the body of the UAV, which has a wingspan of 1.5 m and a nose-to-tail length of 0.8 m.

According to the studies, the *accuracy* of DoA methods is about 2–4°. The accuracy of the relative position estimation with DoA depends on the distance between the vehicles.

The DoA *range* is not strictly limited. However, as the distance increases, the accuracy of the relative position estimation dramatically declines.

The DoA is *vulnerable* to jamming, multipath, and NLoS. The DoA methods require several antennas to be placed separately on the bodies of the UAVs. Therefore, the accuracy of these methods depends on the size of UAVs.

### Line of Sight

Visual navigation (VizNav) methods can be divided into Line of Sight (LoS) and Environmental Observations (EO) methods.

The single LoS methods estimate the LoS vector direction between vehicles from a camera-based image. The scheme of the single LoS method is shown in Fig. 6, *a*, where Image 1 is the image of UAV0 taken by UAV1;  $P$  is the UAV0's position in space;  $P_1$  is the UAV0's position in Image 1;  $O_1$  is the optical center of the UAV1 camera. The LoS vector direction is estimated by the pixel coordinates  $P_1$ .

One of the earliest studies on the LoS method [42] describes a single LoS fusion with DGNSS/INS

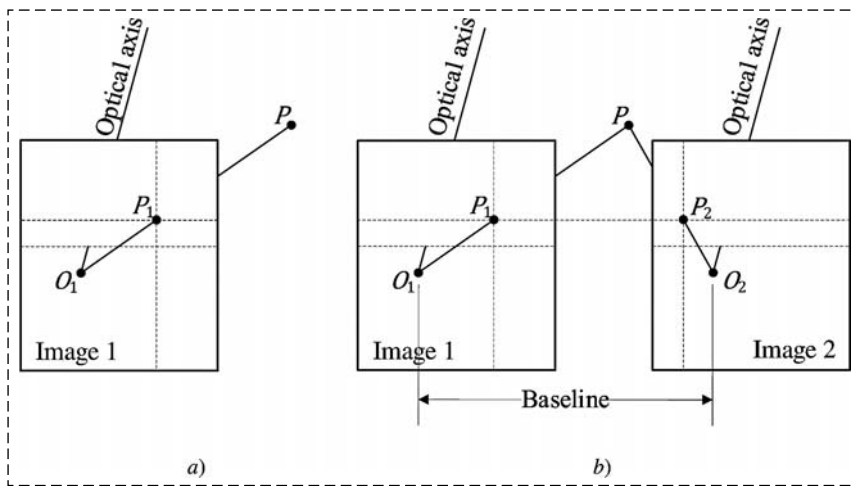


Fig. 6. LoS methods:

a) single LoS method; b) double LoS method [43]

observations. The filtering algorithm has a two-stage structure. The results of the LoS/INS and the DGNSS/INS local filters are fused with the master filter.

Another study [43] describes the double LoS method. Unlike simple LoS, the double LoS method requires at least three vehicles: UAV0, UAV1, and UAV2. The scheme of the double LoS method is shown in Fig. 6, b, where all designations match Fig. 6, a. The relative position of UAV0 can be estimated using the baseline measurements between UAV1 and UAV2.

According to the studies, the *accuracy* of LoS methods is about 0.2 m.

The ability to identify vehicles against the background restricts the LoS *range*.

The LoS *depends* on the time of day and the atmosphere's optical transparency.

### Environmental Observations

The EO methods estimate relative position by matching images of the environment taken by different vehicles. One of the EO methods involves a terrain survey in the nadir. So, the paper [44] describes simultaneously multi-UAV terrain mapping and relative navigation. The proposed method matches feature points between two UAV images using the Scale-Invariant Feature Transform (SIFT) [45]. The scheme of the method is shown in Fig. 7, where the green and blue areas indicate the Field-of-View (FOV) of the UAVs' cameras; the red dots are common feature points in the images. This method resolves four DoFs of a two-UAV system: the relative yaw is estimated by feature orientation, the relative plane position is estimated by

feature pixel coordinates, and the relative height is estimated by the image scale. Another study [46] on the nadir EO method combines it with ToA/INS methods for relative navigation in a GNSS-denied environment.

Another VisNav method, Simultaneous Localization and Mapping (SLAM), is widespread for single UAVs. SLAM algorithms build a three-dimensional environment map and estimate the position of a vehicle relative to this map. SLAM typically employs monocular and binocular cameras to match feature points on captured images.

Applied to multiple UAVs, the SLAM algorithm can be used collaboratively for relative navigation. So, the authors of [47] propose a collaborative SLAM method for two vehicles equipped with monocular cameras. The method fuses SLAM results and INS observations with EKF. The main limitation of the method is the requirement of a permanent overlap of the cameras' FOVs.

In another paper [48], the authors proposed building a global map to improve collaborative SLAM. First, by matching features from several vehicles, a sparse reconstruction of the observed environment is created. This reconstruction is then shared as a global map between the vehicles (Fig. 8). After that, each UAV estimates its own position relative to the global map. Thus, the global map removes permanent FOV overlap requirements. In addition, this method can improve the accuracy of the position estimate compared to a single SLAM. This is possible when one of the vehicles does not observe enough feature points for precise localization.

According to the studies, the *accuracy* of INS/EO methods reaches 0.01 m.

The EO *range* is not strictly limited and depends on camera resolution.

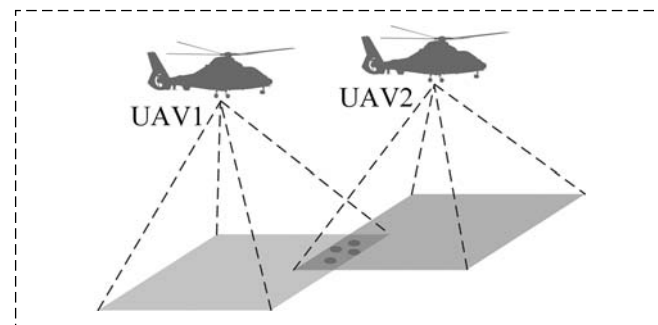


Fig. 7. Nadir EO method [44]

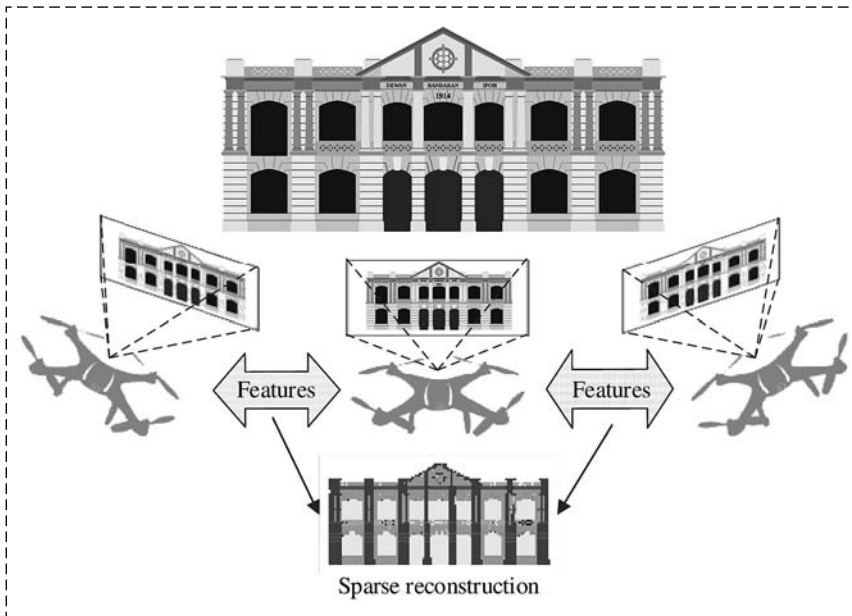


Fig. 8. SLAM EO method [48]

The EO depends on the time of day, the atmosphere's optical transparency, and the environment's visual homogeneity. The EO methods call for extensive computations and data sharing among the vehicles.

### Generic methods

Numerous works focus on generic methods not related to a particular type of sensor [49–51]. One of them [49] suggests a method for integrating UAVs in a sensor network using a variety of sensors, including GNSS and UWB modules, INS, and cameras. This method enables RelNav for a large number

of UAVs and enables measuring the absolute position of vehicles by substituting stationary anchors for a portion of UAVs.

Another paper [50] considers cooperative navigation in an urban environment, independent of the RelNav method. Using GNSS data from multiple vehicles and these relative positions, the virtual centroid position is estimated with increased accuracy. Then, using the known relative positions of the vehicles and the virtual centroid position, the coordinates of each UAV are resolved.

In [51], the authors consider Network Localization and Navigation for mobile nodes. All measurements are classified as intra-node (INS) or inter-node RF-based (GNSS, ToA, RSS, Doppler, DoA). So, GNSS satellites are considered as nodes in the network. In this problem formulation, the RelNav theoretical limitations are determined.

Since the generic methods do not consider certain types of sensors, it is impossible to compare them with other methods.

### Capabilities discussion

The comparative analysis results of the RelNav methods for UAVs are summarized in Table 1. All quantitative values in the table are consistent with the considered works.

Comparative analysis results of the RelNav methods

Method	Accuracy	Range	Disadvantages
Difference GNSS (DGNSS)	0.1 m	no strict limitation	vulnerable to jamming/spoofing/multipath/NLoS; depend on the availability of GNSS satellites
Time of Arrival (ToA)	0.01 m	300 m	vulnerable to jamming/multipath/NLoS; require wideband
Received Signal Strength (RSS)	5 m	N/D	vulnerable to jamming/multipath/NLoS
Doppler shift (Doppler)	0.05 m	1000 m	vulnerable to jamming/multipath/NLoS
Direction of Arrival (DoA)	2-4°	no strict limitation	vulnerable to jamming/multipath/NLoS; depends on the size of the UAVs
Line of Sight (LoS)	0.2 m	limited by a camera	depends on time of day/atmosphere transparency
Environmental Observations (EO)	0.01 m	limited by a camera	depends on time of day/atmosphere transparency; complex calculations and data transmission
Generic methods	depends on types of sensors		

As a result of the review, we formulate the following main capabilities of the RelNav methods:

- The accuracy of most RelNav methods is comparable to Real-Time Kinematic, but it does not require base stations. This capability is advantageous in applications where absolute navigation accuracy is less important than relative navigation accuracy.
- Almost all RelNav methods can work in a GNSS-denied environment. In this case, their accuracy is comparable to GNSS.
- Some methods (e.g., ToA) can be applied to cooperative navigation to improve the accuracy of absolute navigation.
- RelNav can improve collision avoidance. Since RelNav has high accuracy at close distances between vehicles, it can reduce the protection space between vehicles and increase the density of UAVs. In addition, some methods estimate relative position error, which can also be used in collision avoidance [16].

The main disadvantage of all RelNav methods is their limited range. So, all the methods discussed in the review have a maximum range of about one kilometer or significantly degrade in accuracy as the distance between UAVs increases. However, for multi-UAV systems with a short distance between vehicles (about 300 m), this disadvantage is negligible.

## Conclusion

The review offers the RelNav method classification and investigates its capabilities and limitations. We selected 34 research papers for our analysis out of the total number of papers covered. These were the papers that offered the widest variety of RelNav methods. At the same time, the proportion of the selected papers for each type of method to those that were covered for that type is constant.

The differential, RF-based, and visual RelNav methods considered in this paper were developed independently of each other and as part of integral methods. Some studies propose improved RelNav filtering, whereas others consider new combinations of sensors.

Subsequent work on RelNav is likely to be aimed at further improving its autonomy, fault tolerance, and accuracy. We should point out, though, that very few papers focus on the technical aspects of RelNav and the creation of systems that can be used in real-world applications.

RelNav methods for multi-UAV systems can significantly improve these systems' autonomy and

navigational accuracy. However, despite the abundance of papers on RelNav, it is not mentioned in papers that are specifically focused on the applications of multi-UAV systems.

One of the possible reasons for this phenomenon is the lack of off-the-shelf RelNav solutions that could be used in experiments. However, RelNav is not mentioned as a navigation option even in conceptual works that consider theoretical multi-UAV system applications. Therefore, this might suggest that UAV researchers are still unaware of RelNav's capabilities.

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