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Multi-unmanned aerial vehicle multi acoustic source localization

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Abstract

This paper addresses a multisource localization problem with multiple unmanned aerial vehicles equipped with appropriate sensors coordinating with each other, wherein the sources are simultaneously emitting identical acoustic signals. Distributed coordinated localization algorithms based on multiple range and direction measurements are presented and performances are evaluated in different practically significant mission scenarios. Non-deterministic polynomial (NP) hardness to determine optimal number of unmanned aerial vehicles for a given mission scenario is discussed. Group coordination, tactical path, and goal replan strategies to enable efficient localization of single and multiple acoustic sources have been designed. The localization algorithm along with coordination strategy is verified in the presence of realistic error conditions through simulation.

Keywords

Cooperative control, group coordination, group tactical replan, distributed coordinated localization and multi acoustic source localization

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Introduction

The use of unmanned aerial vehicles (UAVs) in military and civilian roles has been growing exponentially since last decade. The features of UAVs such as affordability and expendability facilitate the rapid expansion of operational role from conventional intelligence surveillance reconnaissance (ISR) mission to complex dull, dirty, and dangerous missions. Group autonomy is one of the important area of research, in which multiple solo autonomous UAVs cooperate and coordinate among themselves, without human intervention to achieve a mission.

Autonomous cooperative mission control paves way for many applications and the concept of operations involving multiple UAVs are being evolved. Many military and civilian applications using group autonomy are being conceptualized and pursued by researchers. One such important application of autonomous cooperative mission is on persistent surveillance along border regions. The global requirement is to detect and localize simultaneously emitting multiple synchronous and asynchronous acoustic sources[1–3] near border regions thereby enhancing the situational awareness on the regions of interest.

In this work, multiple sources simultaneously emitting synchronous and asynchronous acoustic signals are considered and the corresponding localization algorithm has been developed. UAV formations yielding best localization performance and UAV trajectory generation and associated coordination strategies are designed to detect multiple acoustic sources. The efficacy of designed algorithm, UAV trajectory, and associated coordination strategies are demonstrated in MATLAB-based simulation package named COPSFLYER for various nominal and off-nominal conditions.

Literature survey

The role of acoustic sensor technology in ground-based, aerial, and naval operations is discussed in

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Kaushik et al.[4] Distributed coordinated localization has been an active area of research in the recent past, and the analysis of relevant literature is summarized below:

Based on conventional methods: Localization of a stationary source based on continuous time estimation,[5,6] vision-based localization,[7] angle of arrival information,[8] bearing angle measurements,[9] time difference of arrival measurements,[10] gradient-based computation,[11] radio frequency (RF)-based geolocation techniques,[12] maximum likelihood algorithm,[13] acoustic source localization in the presence of Echo,[14] under variable speed of sound conditions,[15] and error bounds for localization with noise diversity[16] have been described.

Autonomous control level: A standard for measuring autonomous mission operations is discussed in Suresh and Ghose[17] and it consists of 11 levels. Various standards of group autonomy ranging from group coordination to distributed control are presented.

Cooperative strategy: Localization technique using the range information obtained by multiple onboard receivers,[18] using heterogeneous sensor measurements,[19] based on consensus algorithms,[20] convex optimization,[21] encounter averaging-based approach,[22] bioinspired algorithm,[23] decentralized source localization,[24] network topology for multi-agent system,[25] clock synchronization protocols for wireless sensor networks,[26] time synchronization protocol for sensor networks,[27] cooperative vehicular networking,[28] cooperative localization using direction of arrival measurements,[29] and acoustic target tracking in noisy environments using reconfigurable cluster of mobile agents[30] have been described.

Data association: In Pattipati et al.,[31] Deb et al.,[32] and Popp et al.,[33] it was discussed that the problem of association becomes non-deterministic polynomial (NP) hard when number of UAVs is more than two while localizing multiple synchronous acoustic sources. Heuristic solution by eliminating ghost nodes under ideal measurements,[34,35] with measurement noise[36] and signal selective solution approaches[36–39] are presented.

Experiments: Experimental results employing two dimensional acoustic vector sensor in a distributed network,[40] using unattended ground sensors and UAVs,[41] 3D localization results with a single vector sensor in a shallow water environment,[42] localization performance evaluation on quadcopter,[43] and possible applications[44,45] are discussed.

Motivation and contribution

Motivated by the fact, that the work reported in literature is aimed at addressing specific problems pertaining to cooperative localization, this work aims at revisiting and classifying existing algorithms with their merits and demerits, presenting novel localization algorithms and to provide an integrated solution for multi-UAV multisource distributed cooperative localization in a dynamic environment. The contributions of this work are as follows:

a. Performance evaluation of existing and proposed algorithms for different practically significant mission scenarios.
b. Generation of ready reckoner for employing the best algorithm for a given mission scenario.
c. Development of computationally efficient ghost node elimination algorithm for synchronized multiple sources.
d. Cooperative trajectory design for ghost node avoidance and for achieving maximum coverage in different source configuration.
e. UAV group coordination, tactical path, and goal replan strategies for static and dynamic source localization.
f. Mission simulation under nominal and off-nominal conditions with realistic errors.

Our present work enhances the scope of the work reported in literature by addressing the problem of multi-UAV multisource coordinated localization in an integrated manner. The rest of this paper is organized as follows: Acoustic source dissipation pattern section discusses acoustic source dissipation, Algorithm to localize synchronized and asynchronized static source emission section presents the algorithms to localize synchronized and asynchronized static source emissions, Mission configuration and its significance section discusses mission configuration and its significances, and Performance evaluation of algorithms for different practically significant mission scenarios section presents the performance evaluation of algorithms for different practically significant mission scenarios. Section Cooperative mission trajectory design discusses the cooperative mission trajectory design, Error modeling section discusses the error modeling, Mission simulation results on a border surveillance mission scenario section presents the mission simulation under nominal and off-nominal conditions with realistic errors, and Conclusions section presents the conclusion.

Acoustic source dissipation pattern

Sound waves are generated by the vibration of any solid body in contact with the fluid medium or by vibratory forces acting directly on the fluid. Vibrating objects usually produce sound in different radiations such as monopole, dipole, quadrupole,[46] which represent the acoustic directivity patterns encountered in a battlefield environment. For example, a gun shot[47] can be characterized as a monopole source and a tank movement in a rough terrain can be characterized by dipole or combination of both monopole and dipole sources. In this paper, without loss of generality, monopole source is used to represent the dissipation pattern of acoustic source.

A monopole is a source which radiates sound equally well in all directions and creates a sound wave by alternately introducing and removing fluid into the surrounding area. The amplitude of pressure at some distance for a monopole is given by

$$|p(r)| = \rho c \frac{Qk}{4\pi r} \tag{1}$$

where p = pressure [pascal], r = distance [meters], ρ = density of air [kgm^{-3}], c = speed of sound [ms^{-1}], k = wave number [m^{-1}], and Q = source strength [m^{3}s^{-1}].

This paper assumes that each of UAV is equipped with an acoustic vector sensor. Acoustic vector sensor[48] used by the simulated UAVs employs four channels and it consists of a nondirectional sound pressure microphone, and three orthogonal acoustic particle velocity sensors, each of which is sensitive in one direction. The ratios between the intensity of signals are used to instantly determine the direction of the source independent of frequency. Depending on the measurement technique employed, sensor produces output either as propagation direction (angle of arrival) or propagation distance (time difference of arrival, frequency difference of arrival, power difference of arrival).

Algorithm to localize synchronized and asynchronized static source emission

Localization is a method to determine the acoustic source position by establishing the spatial relationship by the known measurements (observations) and unknown parameters. This section discusses the existing methods and our proposed methods for localization of single and multiple acoustic sources.

Single source localization: Conventional method

The following algorithms are well known and established methods for single source localization.

Triangulation and trilateration. Triangulation method[49] determines the location of a source using angle of arrival measurements of two sensors using line of bearing. Trilateration method[49] uses three sensor-to-source range measurement to uniquely localize any source in a two-dimensional plane. For a given N_U number of UAVs, triangulation is computationally less expensive than trilateration as it requires solving system of linear equations.

Linear least squares and maximum likelihood estimator. These techniques improve the localization accuracy in the presence of noise. Linear least squares (LLS) [49] technique determines the source position by minimizing the square of the distance between the estimated and measured line of bearing (LoB). Maximum likelihood estimator (MLE)[50] uses range difference of arrival measurements to localize a source by minimizing the maximum likelihood cost function. The error in the range measurements is usually considered as zero mean Gaussian and independent of each other.

Multiple source localization: Conventional method

Brute force method. While localizing the synchronized multiple sources, the problem of data association (unknown correspondence of measurements to sources) is encountered. In this method, it is resolved by performing exhaustive search over the set of all possible combinations to localize multiple sources.[49]

Clustering algorithm. In multisource multi-UAV scenario, intersection points of LoBs are clustered by k-means algorithm[49] and centroids of the clusters represent positions of sources. This algorithm outperforms brute force method in terms of computational efficiency; however, its accuracy degrades because of the presence of ghost nodes.

Our contributions on localization algorithm

1. MAP method for single source localization. In a typical battlefield scenario, UAVs are operating at different altitudes to perform intelligence, surveillance, and reconnaissance missions. The UAVs operating relatively at higher altitudes have larger foot prints on the area of interest. Upon image exploitation, potential source of interest, its location, and signature are identified with band of uncertainty. The processed information is provided to tactical UAVs, which are operating at relatively lower altitudes, to perform close range reconnaissance around the objects of interest. Because of the availability of a priori information on the probable location of the acoustic sources, maximum a posteriori (MAP) method[51] can be employed to improve the localization accuracy of ML estimate. MLE, as discussed in Stephen,[50] requires range difference of arrival (based on range measurements) for localization where as MAP requires additional prior information on source position. The cost function (J) for MAP estimation consists of two terms, the first one represent MLE cost function[50] and the second one is from prior information, modeled as bivariate Gaussian density with mean $\underline{\mu}$ and variance–covariance matrix σ_{sqr}. Therefore

$$\begin{aligned} J_{MAP}(\underline{s}) &= J_{ML}(\underline{s}) + J_{prior}(\underline{s}) \\ &= h^T(\underline{s})\Sigma^{-1}h(\underline{s}) + (\underline{s}-\underline{\mu})^T\sigma_{sqr}^{-1}(\underline{s}-\underline{\mu}) \end{aligned} \tag{2}$$

where

$\underline{s}$ = Unknown source position
$J_{MAP}(\underline{s})$ = MAP cost function

$J_{ML}(\underline{s})$ = MLE cost function
$J_{prior}(\underline{s})$ = Prior information cost function
$h(\underline{s})$ = Range difference of arrival error vector
Σ = Noise covariance matrix
μ = Prior information mean
σ_{sqr} = Prior information variance – covariance matrix

The source position is estimated by minimizing the cost function indicated in equation (2)

$$\hat{\underline{s}}_{MAP} = \arg\min J_{MAP}(\underline{s}) \tag{3}$$

In a realistic scenario, range measurements are prone to errors[52] and error in range difference of arrival is modeled as Gaussian noise with zero mean and standard deviation of 10 m. In our study, UAVs are assumed to have an acoustic sensor upto 3.5 km range and measurement standard deviation is assumed to be 0.2% of this range. Prior information on the source position is modeled as normally distributed random vector with standard deviation of 5 m. It is assumed that high altitude surveillance platform geo-localizes the target of interest with a standard deviation of 5 m. The performance of MAP algorithm depends on the quality of the prior information.

A mission scenario involving UAVs in circular formation (with equal angular separation) to localize the source position which is positioned at the center of a circle (0,0) is considered to evaluate the performance of MLE and MAP. The performance was evaluated using different number of UAVs ranging from 8 to 36 corresponding to equal angular separation of 45° and 10°, respectively. Figure 1 corresponds to an error condition within one sigma error bound in range difference of arrival and with different prior information on true source position, which is normally distributed with mean at (0,0), (−0.5, −0.5), and (−1, −1) and the estimates are referred henceforth MAP1, MAP2, MAP3, respectively. Figure 2 corresponds to error condition within 10 sigma error bound in range difference of arrival and with prior information same as above. The following can be inferred from these two figures

a. As the number of participating UAVs in the cooperative mission increases, difference of MLE and MAP estimate decreases.
b. Due to availability of prior information, MAP performance is better than MLE and this trend is consistent with increase in number of UAVs.
c. Larger dispersion in prior information has impact on MAP performance as the algorithm tries to converge toward the prior information. For a prior information with mean at true source position, MAP algorithm yields the lowest estimation error and this trend is consistent with increase in participating UAVs.
d. Non-monotonic behavior of estimation error is entirely due to addition of random error to all measurements for each UAV configuration. However, for any given UAV configuration, MAP algorithms yield lower estimation errors in comparison to MLE algorithm and it is consistent with increase in number of UAVs.

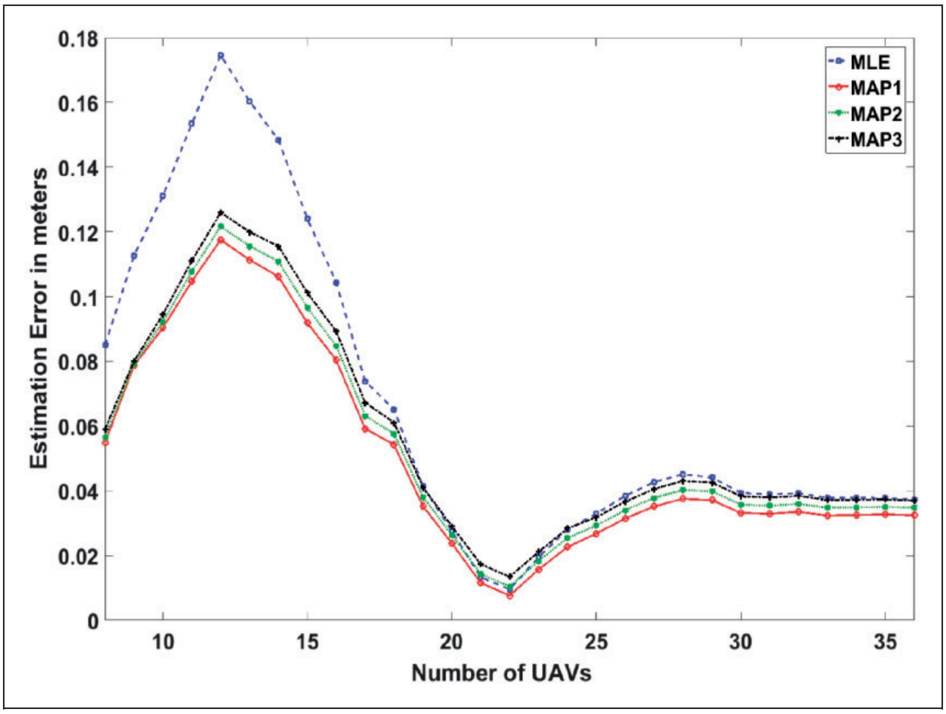

Figure 1. MAP and MLE performance (1 sigma range difference measurement error).

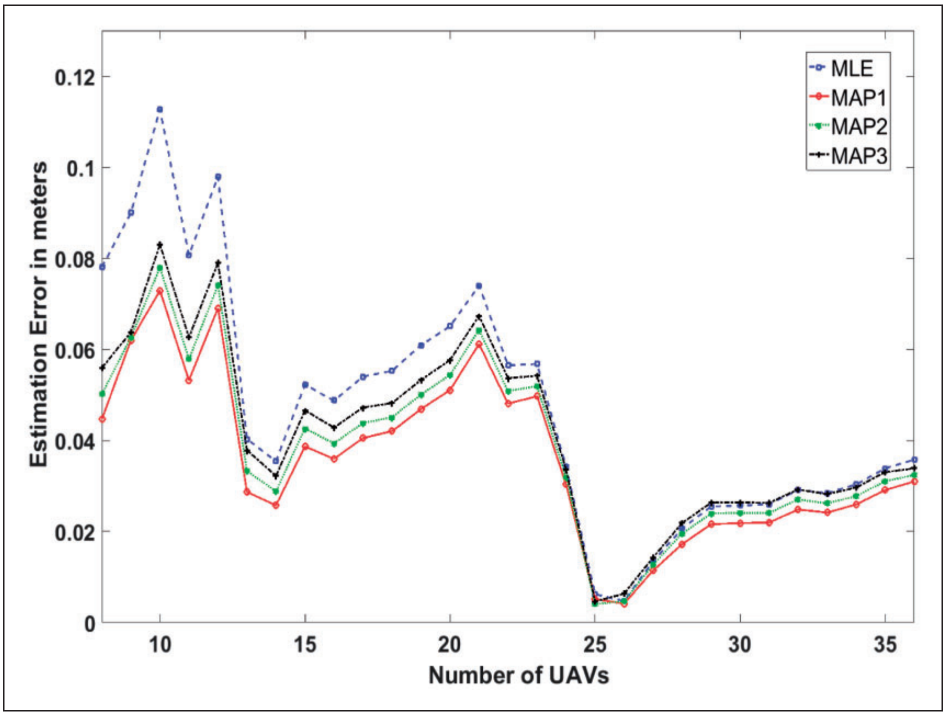

Figure 2. MAP and MLE performance (10 sigma range difference measurement error).

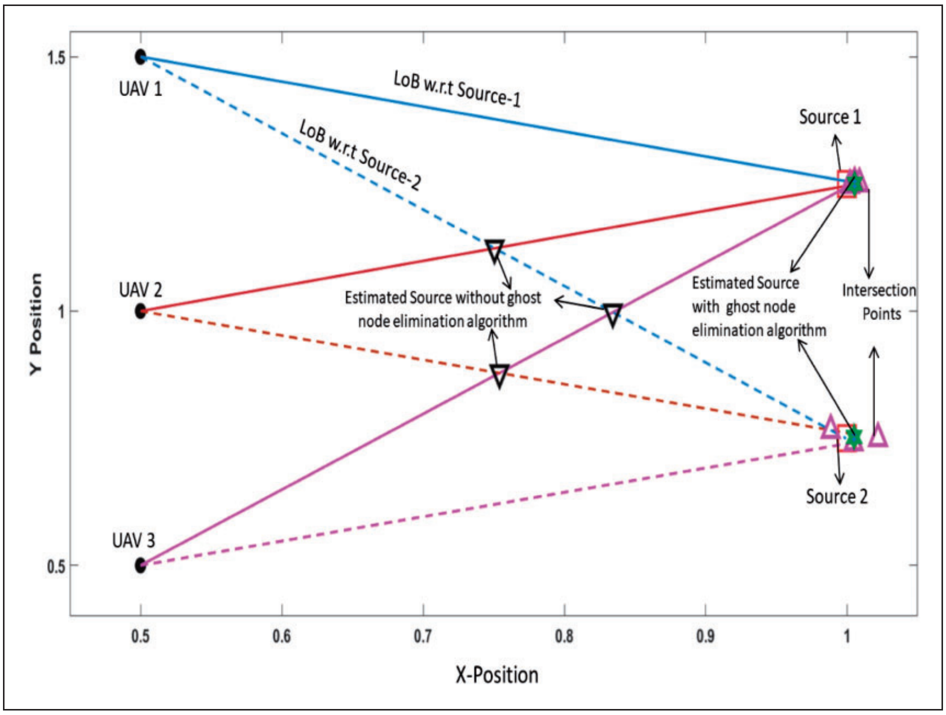

Figure 3. Localization in presence of ghost node elimination algorithm.

Even with a mean of $(-1, -1)$ in the prior information, MAP algorithm performance is better than MLE and this trend is consistent with increase in number of participating UAVs. Thus, MAP algorithm is preferable to MLE for single source localization in the presence of reasonable prior information.

2. Ghost node elimination for synchronized multiple sources. In a scenario in which multiple UAVs are used to localize multiple sources that are synchronously emitting acoustic signals, often ghost nodes are encountered. For example, consider the scenario shown in Figure 3, where three UAVs are employed to localize two sources. The LoBs from each of the three

UAVs intersected at nine points, which represents likely positions of the sources, but, there are only two actual sources. The intersection points near the actual source and also the ghost nodes are shown with appropriate markers. When localization is done considering all intersection points including ghost nodes as valid, it results in localization of sources, which are much farther from the actual source position.

Ghost node elimination algorithm: We proposed a computationally efficient ghost node elimination algorithm (Algorithm 1). The function *Find Intersection* determines all possible intersection points for a given number of UAVs and sources. The presence of physically impossible intersection points, which are present due to the UAV and source configuration, is determined by *Find Feasible Intersection* function. The function *Find Calculated time of arrivals (TOAs)* determines the time of arrival from each feasible intersection point to corresponding UAVs and the function *Find time difference of arrivals (TDOAs)* estimates the time difference of arrival between measured TOAs and calculated TOAs. The function *Find Invalid Intersection* compares TDOAs with specified tolerance level and generates invalid intersection points. The function *Apply Ghost Elimination* removes invalid intersection points from the set of all feasible intersection points.

Clustering method is applied on these final intersection points to obtain the source location. The source position obtained using ghost node elimination lies closely with actual source position indicated as square. This algorithm is scalable and can be effectively used for localizing higher number of multiple sources emitting synchronously. The proposed algorithm eliminates the ghost node with running time function proportional to square of number of sources for a constant number of UAVs in comparison to running time function proportional to cube of number of sources for a constant number of UAVs as discussed in Reed et al.[36]

Cooperative trajectory to avoid ghost node: An alternate method to avoid ghost nodes is through cooperative path and trajectory planning. In a mission scenario, where the acoustic sources, its position and velocity, are known with a band of uncertainty, cooperative path, and trajectory planning can be employed to avoid ghost node to achieve better localization accuracy. Consider a scenario as shown in Figure 4, in which UAVs are flying colinearly with each other. If only two sources are placed perpendicular to the instantaneous heading of UAVs, ghost nodes will not be encountered as the LoB's won't intersect with each other. Hence, the localization of sources becomes relatively simpler due to the absence of ghost nodes. However, this UAV and source configuration cannot be guaranteed at all time as the UAVs need to change their trajectories dynamically to exploit pop-up sources, avoid obstacles, and evade risk zones. Even though ghost node can be avoided through careful mission planning, it is essential to equip all the participating UAVs with ghost node elimination algorithm and also employ cooperative trajectory planning, to achieve desired localization accuracy in a dynamic battlefield scenario.

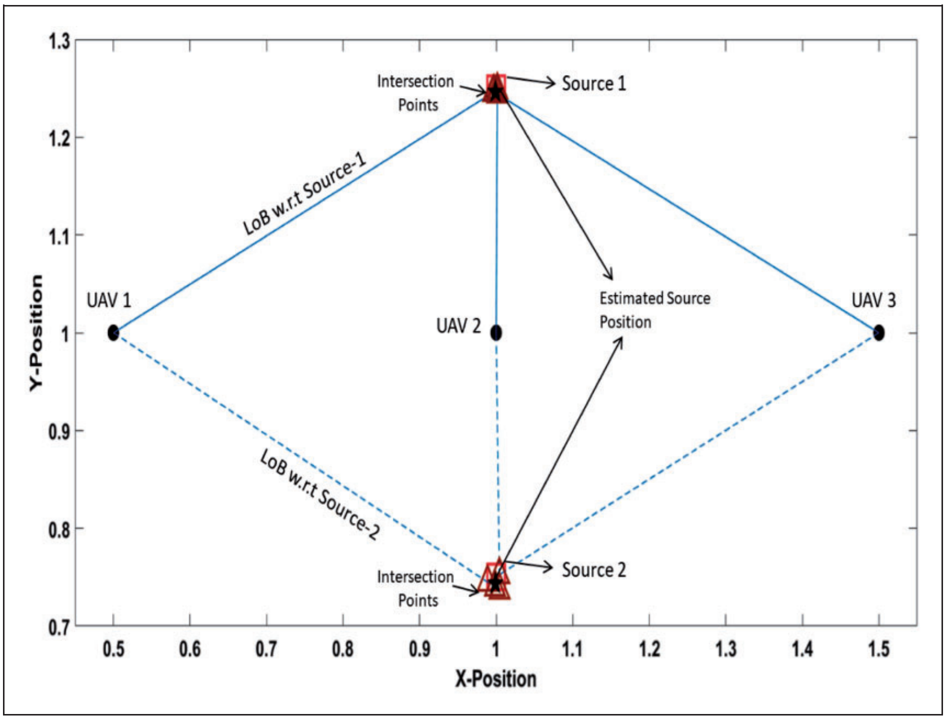

Figure 4. Ghost node avoidance using cooperative trajectory.

Algorithm 1. Ghost node elimination algorithm

Require:
Number of UAVs $\{N_U\}$, Number of Sources $\{N_S\}$
Tolerance for valid intersection $\{T_{tol}\}$, Speed of sound $\{c\}$
Measured TOAs $\{TOA_{meas}\}$
Ensure:
Valid intersection points $\mathcal{I}_V^*$

1: $\mathcal{I}_{raw} \leftarrow$ *Find Intersection* $(\{N_U\}, \{N_S\})$
2: $\mathcal{I}_{feas} \leftarrow$ *Find Feasible Intersection* $(\{N_U\}, \{N_S\}, \{I_{raw}\})$
3: $\mathcal{TOA}_{calc} \leftarrow$ *Find Calculated TOAs* $(\{N_U\}, \{I_{feas}\}, \{c\})$
4: $\mathcal{TDOA}_{est} \leftarrow$ *Find TDOAs* $(\{TOA_{calc}\}, \{TOA_{meas}\})$
5: $\mathcal{I}_{inval} \leftarrow$ *Find Invalid Intersection* $(\{TDOA_{est}\}, \{T_{tol}\})$
6: $\mathcal{I}_V^* \leftarrow$ *Apply Ghost Elimination* $(\{I_{feas}\}, \{I_{inval}\})$

3. Clustering for single source localization. In a multi-UAV single source localization scenario, multiple LoB measurements are obtained from various sensors. One simple and more useful technique to fuse noisy measurements for source localization in comparison with triangulation is clustering of intersection points of LoBs, which are measured against a source. This is an application of clustering algorithm (CLA) (as discussed in Multiple source localization: Conventional method) for single source scenario and it does not suffer from presence of ghost nodes as in synchronized multiple sources.

In order to analyze the performance, a mission scenario involving localization of source where UAVs are positioned in a circular pattern is considered. This is selected such that the operating radius (UAV distance to source) is invariant with respect to increase in number of UAVs when positioned in circular pattern, thereby avoiding effect of range on performance. In a practical scenario, LoB's measurements are prone to measurement error, which needs to be realistically modeled and included in the performance analysis. Measurement noise is modeled as zero mean Gaussian density with 0.02 radian standard deviation. For illustration of performance, three error sets are generated considering $\pm 3\sigma$ condition. These error sets are added along with actual LoBs to generate measured LoBs. Performance of LLS and clustering for different number of UAVs is shown in Figure 5 for the above generated error sets. It can be inferred that CLA performance is comparable to LLS in terms of Euclidean distance error between estimated and true position and performance observed is consistent among three error sets.

As the performance of clustering method is comparable to LLS, CLA is preferred as the same algorithm can also be used for synchronized multiple

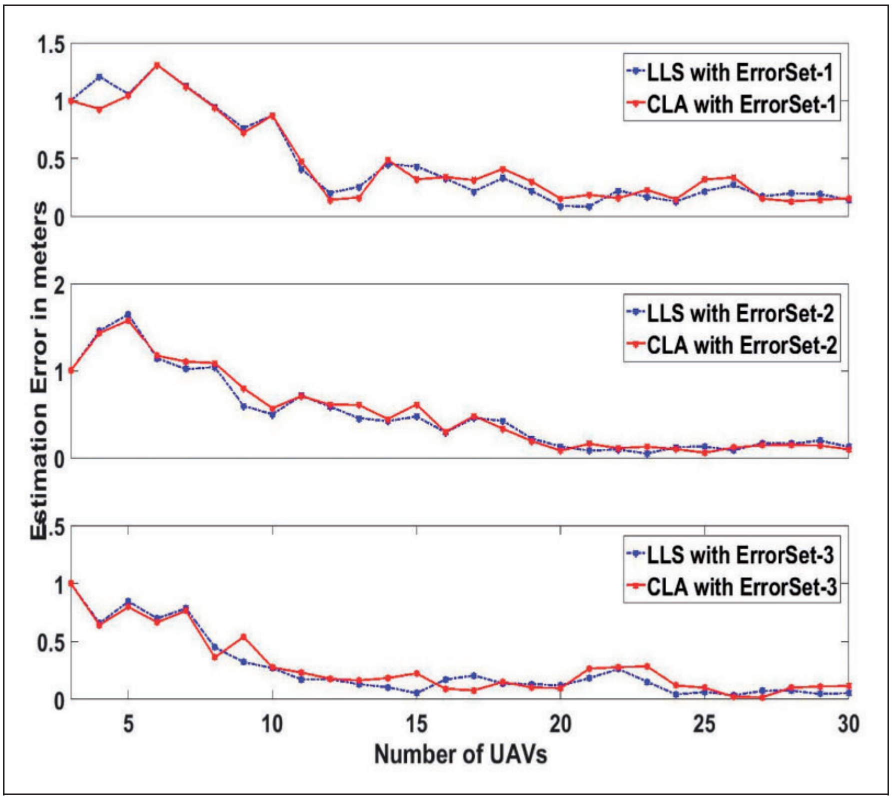

Figure 5. Performance comparison of LLS with clustering algorithm (3 sigma error condition).

sources. Real-time implementation will be easier, as this algorithm caters for both single and multi source localization.

Mission configuration and its significance

In a group autonomy (level 5 of autonomous level), UAVs need to cooperate and collaborate in a coordinated manner to achieve the goals of a complex mission. Spatial and temporal coordination procedures demands participating UAVs either to follow circular or straight line formation. The primary formation along with sub-formations is shown in Figure 6 and the UAVs can take any one of these formations during the mission. These formations can be broadly classified into three types during the mission as follows:

Equidistant: During cooperative UAV source engagement, often the position of the source of interest and its defence capability is known within a band of uncertainty. Cooperating UAVs make a circular formation at a stand-off distance, around the source, with the intention of localizing sources.

Colinear: During formation reconfiguration (transition to new formation to perform mission or to adapt to UAV failures), cooperative UAVs may encounter colinearity with respect to source of interest.

Overlap: In order to achieve spatial and temporal coordination procedures in a collision/obstacle-free environment, it is essential for cooperating UAVs to stack themselves one over above (vertically), to pass through a narrow passage. In this configuration, the cooperative UAVs overlap with the source of interest.

Performance evaluation of algorithms for different practically significant mission scenarios

The performance of single source localization algorithms using multiple UAVs (as described in Algorithm to localize synchronized and asynchronized static source emission section) was verified for different mission scenarios (as described in Mission configuration and its significance section) and the results are shown in Figure 7. The scenarios are decided based on the UAV-source configuration that are encountered during the missions execution. The suitability and non-suitability of algorithm against each mission scenario configuration is indicated by tick and cross mark, respectively. The following can be inferred:

a. MAP algorithm is suitable for all mission scenario configurations. This is because of a priori (probable location of sources) information of the source location.
b. Triangulation, clustering and LLS method are not suitable for two conditions (sensors overlap with each other, sensors and source are collinear). This is because, in above conditions, all the LoB's measurements are same leading to no solution.
c. MLE is suitable only for two conditions (sensors are collinear, sensors and source are collinear with each other). This is because, in all other conditions, all the range measurements are same leading to zero range difference of arrival and hence no solution.
d. Triangulation is not suitable for equidistant (on axis) case because direction of arrival measurement with respect to source under error-free conditions can exactly be 0, 90, 180, or 270°. However, if the measurements include 90 or 270°, solution cannot be obtained as tangent function for these angles are undefined. Before applying localization algorithm, these conditions must be determined and excluded. Similarly, if the measurements include only 0 and/or 180°, then no unique solution exists as it is a special case of colinearity. In this case, the angular measurements require dithering[53,54] to produce reasonable solution.
e. Trilateration is not suitable for sensors in colinear case, sensors overlap with each other, sensors and source are colinear, because the straight lines represented by families of linearized equations are parallel leading to no solution.

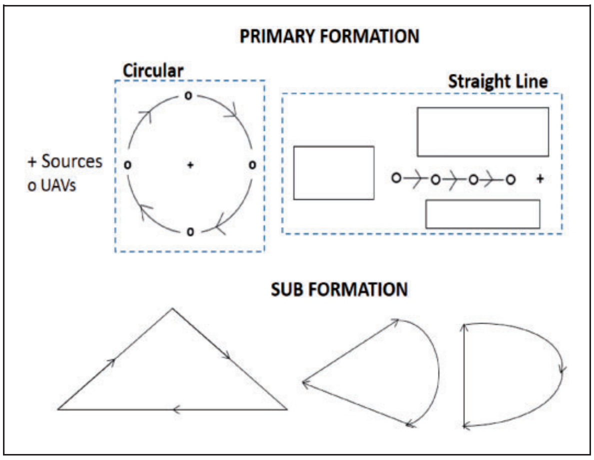

Figure 6. Primary and sub formation.

The performance of multisource localization algorithms using multiple UAVs (as described in Algorithm to localize synchronized and asynchronized static source emission section) was verified for various mission scenarios (as described in Mission configuration and its significance section) and the results are shown in Figure 8. The suitability and non-suitability of algorithm against each mission scenario configuration is indicated by tick and cross mark respectively. It can be inferred that CLA is not suitable when sources are placed in-between UAVs position as sources and UAVs are colinear, generated

Scenarios	Triangulation	Trilateration	Clustering	LLS	MAP	MLE
Sensors colinear	✓	X	✓	✓	✓	✓
Sensors and target collinear (Equal dispersion around target)	X	X	X	X	✓	✓
Sensors and target collinear (Unequal dispersion around target)	X	X	X	X	✓	✓
Sensors overlap	X	X	X	X	✓	X
Equidistance (Four quadrants)	✓	✓	✓	✓	✓	X
Equidistance (on axis)	X	✓	✓	✓	✓	X
Equidistance (one quadrant)	✓	✓	✓	✓	✓	X
Equidistance (two quadrant)	✓	✓	✓	✓	✓	X

Figure 7. Single source multi-UAV algorithm performance comparison.

Scenarios	Brute Force algorithm	Clustering algorithm
Equidistance : When sensors are placed at same distance between the targets	✓	✓
Co-linear Case 1 : Targets are placed parallel with respect to the sensors position	✓	✓
Co-linear Case 2 : Targets are placed perpendicular with respect to sensors position.	✓	✓
Co-linear Case 3 : Targets are placed in between sensors position.	✓	X

Figure 8. Multisource multi-UAV algorithm performance comparison.

line of bearing may intersect at a point which is very far from true source position. Though this phenomena can be avoided by designing proper algorithm, for this case, it will result in insufficient number of valid intersection points for clustering. Hence, cooperative trajectories during mission involving colinear UAVs should be avoided.

Range sensitivity analysis has been carried out in order to analyze the impact of range on algorithm performance and it is done by increasing the distance of each UAV from the source position. For single source multi-UAV scenario, as the distance between UAVs and source increases, error in estimation increases for clustering and LLS method. This is because, the offset (perpendicular distance of the source from line of bearing) increases with increase in range. This phenomena is observed in multisource multi-UAV scenario for both clustering and brute force method. Hence, during cooperative mission, LoB-based localization shall be attempted at close range to minimize range-sensitive error. However, range-based localization algorithms are not sensitive to range to source.

Cooperative mission trajectory design

Single UAV single static source localization

Consider a scenario in which a static source emitting continuous omnidirectional acoustic signals and a UAV equipped with a sensor suite consisting of LoB and range to source measurement sensors. If a single

UAV executes a circular trajectory around the source at a safe standoff distance, the onboard sensor suite either measures the acoustic signal angle of arrival or measures its range to source or both. The onboard computer stacks these time-stamped measurements and solve the localization algorithm as described in Algorithm to localize synchronized and asynchronized static source emission section to obtain the source location. The same philosophy can also be employed to localize static source (discrete) that emits acoustic signals at specified intervals.

Single UAV single mobile source localization

In this scenario, to localize a mobile source, three measurements from a single UAV, at three different positions within a short span of time are required. Let V_u and ρ_u be the linear and angular velocity of UAV. Let V_{ms} and ρ_{ms} be the linear and angular velocity of mobile source. A single UAV can localize mobile source if the following two conditions are satisfied.

$$\frac{V_{ms}}{V_u} << 1 \tag{4}$$

$$\frac{\rho_{ms}}{\rho_u} << 1 \tag{5}$$

If the speed of the mobile source is much less than the speed of the UAV, then the dispersion in localized mobile source position, using three distinct measurements gathered at three different positions, with respect to source true position, is almost negligible.

Multi-UAV single static/mobile source localization

During cooperative mission, multiple UAVs form a geometric arrangement around static/mobile source, as shown in Figure 6. Both discrete and continuous sources can be localized based on single measurement obtained from all participating UAVs.

Single UAV multi static source localization

Consider a scenario in which a series of static sources emitting continuous omnidirectional acoustic signals are placed at equal distances and an UAV equipped with a sensor suite consisting of angle of arrival and range to source measurement sensors. The objective is to maintain maximum observability (maximum coverage by sensor) on each of the acoustic sources by following appropriate trajectory. One of the locomotion mode snake follows is an lateral undulation trajectory,[55] in which waves of lateral bending are propagated along the body from head to tail. One complete full cycle of lateral undulation trajectory (measured from crest to crest) is refereed as snake trajectory in rest of this paper.

If a single UAV (as shown in Figure 9) executes a snake trajectory around these sources ensuring a safe standoff distance, the onboard sensor suite either measures the acoustic signal angle of arrival or measures its range to source or both. The onboard computer stacks these time-stamped measurements, collate these measurements (Algorithm 2), and executes the localization algorithm as described in Algorithm to localize synchronized and asynchronized static source emission section to obtain all the source locations.

The same philosophy can also be employed to localize the source, emitting discrete acoustic signals. In general, the UAV can localize a source if at least three measurements are obtained from a single source within one-half of snake trajectory. For this, the sensor measurement range should be more than intra-separation distance between two static source locations.

Two UAV multi static source localization

In the previous scenario, if UAVs are cooperatively following the predefined snake trajectory, one UAV from head to tail and another UAV from tail to head, at the same speed, it results in more number of measurements, which can be collated (Algorithm 2) with respect to source locations. These measurements are used to solve the localization algorithm as described in Algorithm to localize synchronized and asynchronized static source emission section to obtain the source locations. In this scenario, UAV sensor suite can complement with each other with one UAV equipped with angle of arrival sensor and another with range to source sensor.

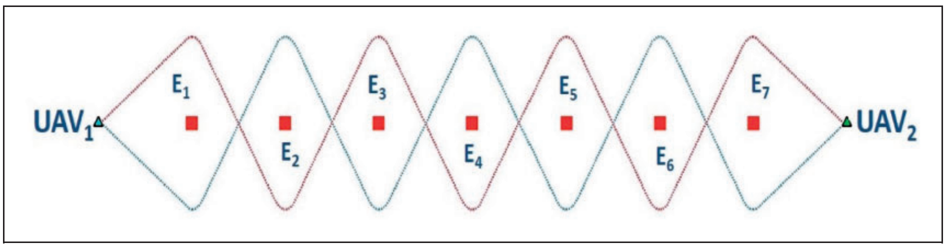

Figure 9. Two UAVs following snake trajectory (starting from UAV 1 and 2) providing maximum observability.

Multi UAV two mobile source localization

Consider a scenario, in which, two mobile sources (Γ_j, Γ_{j+1}) maintaining fixed distance ($\rho_d = ||\Gamma_{j+1} - \Gamma_j||$) are emitting acoustic signals asynchronously, while moving at constant velocity or at constant acceleration. Two UAV teams, each consisting of three UAVs ($U_i\ \forall\ i = 1 \ldots 3$), are following a predefined trajectory to localize each of sources separately based on three associated measurements from each source. Let $\chi_{\max}$ and $\Pi_{\max}$ denote the maximum sensing and communication range. In this scenario, even a single UAV team can localize both sources, if these UAVs follow a trajectory satisfying the following *Localizability* criterion.

A. Communication constraint

$$
\begin{aligned}
&||U_i - U_{i+2}|| \leqslant \Pi_{\max} \text{ AND } ||U_i - U_{i+1}|| \leqslant \Pi_{\max} \text{ OR} \\
&||U_i - U_{i+1}|| \leqslant \Pi_{\max} \text{ AND } ||U_{i+1} - U_{i+2}|| \leqslant \Pi_{\max} \text{ OR} \\
&||U_i - U_{i+1}|| \leqslant \Pi_{\max} \text{ AND } ||U_{i+1} - U_{i+2}|| \leqslant \Pi_{\max} \text{AND}
\end{aligned}
$$

B. Sensing constraint

$$
\{\text{Max}\{||U_i - \Gamma_j||,\ \forall i = 1 \ldots 3\} + \rho_d\} \leqslant \chi_{\max}\}
$$

In case of synchronous emission of acoustic signals, still the source can be localized by applying data association techniques[49] on measured inputs.

Multi-UAV multi mobile source localization

In a complex dynamic environment, multiple mobile sources occur simultaneously in a given regions of interest, which needs to be cooperatively localized by UAVs. From the earlier discussion, we know that minimum of three UAVs are required to localize a source and are enough to localize two sources, if UAVs are placed appropriately satisfying *localizability* criterion.

For a given region of interest, mission commander would like to deploy minimum number of UAVs to localize multiple sources. For a given M number of acoustic sources on a given region of interest, determining minimum number N of UAVs that satisfies *localizability* criterion depends on the mission scenario and also the presence of en route surprises and events during the mission.

Theorem 1. Determination of minimum number of UAVs to localize synchronous mobile sources satisfying *Localizability* criterion in a complex dynamic environment is NP hard.

Proof. Consider a scenario with N_U and N_S number of UAVs and sources. One trivial localization solution is to generate N_S number of UAV team, each team comprising of three UAVs and assign to N_S number of sources. But, our goal is to determine minimum number of UAVs to localize all N_S number of sources, satisfying localizability criterion. The following optimization problem is formulated

$$
\begin{aligned}
&\text{Minimize} \sum\nolimits_{i,k} \mathbf{M}_{ik} \\
&\text{Subject to} \sum\nolimits_{i,k} \mathbf{A}_{ikj} \geqslant 3 \\
&\sum\nolimits_{m,p;n,q \in \left\{ i,k | \sum_{i,k} \mathbf{A}_{ikj} \geqslant 3 \right\} \forall j,\, mp \neq nq} C_{mp;nq} \geqslant 3 \\
&\forall i, j, m, n \in \{1, \ldots N_T\} \text{ and } \forall k, p, q \in \{1, \ldots N_U\}
\end{aligned}
$$

$\mathbf{M}_{ik}$ is a decision variable, 0 by default, takes 1, if kth UAV is positioned for source i; $\mathbf{A}_{ikj}$ is 0 by default and takes 1, if kth UAV meant for source i, also covers source j; and $C_{mp;nq}$, 0 by default, takes 1, if pth and qth UAV are in communication range.

This problem is a set multi-cover problem with additional communication constraint. Set multi-cover problem is a well-known NP hard problem and the problem of determining minimum number of UAVs to localize synchronous mobile sources satisfying *Localizability* criterion is also NP hard.

Theorem 2. For a given configuration of sources, an UAV following snake trajectory provides maximum observability on each of the sources.

Proof. A scenario involving sources $(E_1, E_2, \ldots, E_n)$ located co-linearly at a fixed intra-separation distance of $2R$ from each other is considered. The objective of an UAV is to follow a trajectory $T(t)$ that ensures maximum observability (coverage) on each of the sources.

One candidate trajectory that ensures maximum observability is a circular trajectory which can be expressed as $T(t) = (U_x - E_{ix})^2 + (U_y - E_{iy})^2 - R$, where (U_x, U_y) and (E_{ix}, E_{iy}) denote the position of UAV and source respectively and R denotes the minimum turn radius of UAV. This can be achieved by commanding UAV to execute bank angle at its minimum flyable velocity (V_m) to cover total distance of 2πR, which can be expressed as $\phi_c(t) = \arctan(V_m^2/gR)$.

Applying constraint of $T(t, E_1)|_{entry} \neq T(t, E_1)|_{exit}$ ensures that UAV total distance travel is less than 2πR. Applying another constraint of $T(t, E_1)|_{exit} = T(t, E_2)|_{entry}$ ensures that UAV traveled equal πR distance on both sources E_1 and E_2. Both these constraints can be met by commanding the bank angle of same magnitude with alternate sign for every πR distance.

$$
\phi_c(t) = \begin{cases} \arctan(V_m^2/gR) & \text{for} \quad n\pi R \quad \forall n = 1, 3, 5 \ldots \\ -\arctan(V_m^2/gR) & \text{for} \quad m\pi R \quad \forall m = 2, 4, 6 \ldots \end{cases}
$$

The trajectory corresponds to bank command $\phi_c(t)$ represents the snake trajectory and it provides maximum observability on each of the sources. The possible variants of the above scenario are all the sources are located randomly while maintaining intra-separation distance of either $2R$ or less or more than $2R$.

The combination of above two cases leads to more generalized case of random placement of sources on a given area and UAV has to provide maximum coverage on each of the sources. This objective can be achieved by segmenting the given area of interest into circular cells (as shown in Figures 10 and 11) of minimum turn radius of UAV. UAV follows the snake trajectory (Figure 10) as stated above and provides maximum coverage on each of the sources in the given area of interest. Full coverage in shorter time is achievable when more than one UAV cooperate (Figure 11) with each other, following circular trajectory on the area of interest.

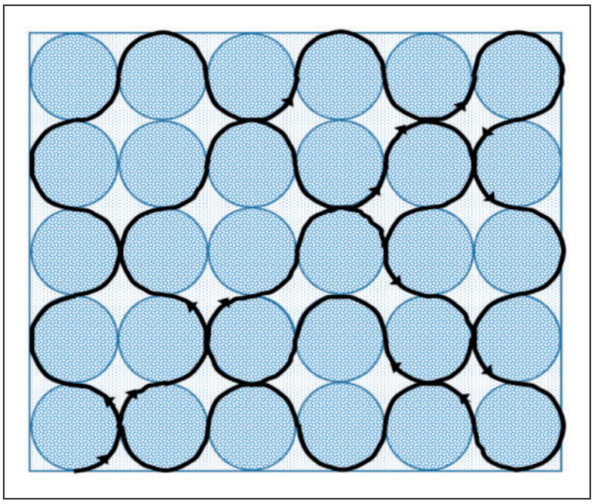

Figure 10. Snake trajectory of single UAV covering area of interest.

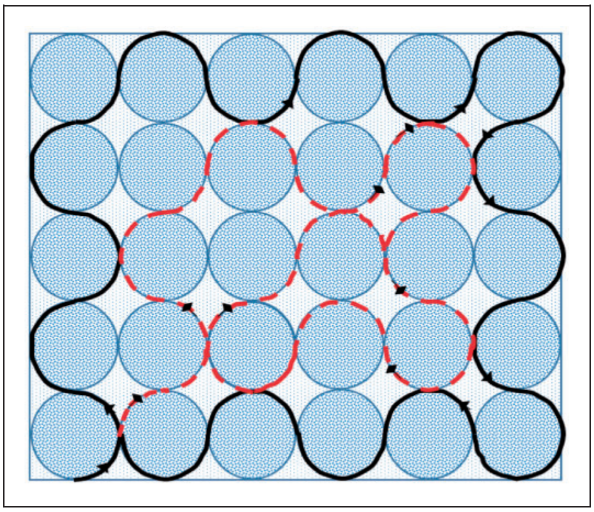

Figure 11. Snake trajectory of two UAVs covering area of interest (solid line with arrow representing one UAV and dashed line with diamond arrow representing another UAV).

Algorithm 2 Algorithm to collate the source based measurements

Require:
Set containing maneuvers $\{M_{an}\}$
Set containing measurement and time vector $\{M\}$ and $\{\tau\}$
Set containing associated positions $\{X_{pos}\}$ and $\{Y_{pos}\}$
Ensure:
Measurements associated with each source $\mathcal{M}^*$

$[\mathcal{P}_{Srt}, \mathcal{P}_{End}] \leftarrow$ *Extract Port Start and End* $(\{M_{an}\})$
$[\mathcal{S}_{Srt}, \mathcal{S}_{End}] \leftarrow$ *Extract Starboard Start and End* $(\{M_{an}\})$
$[\mathcal{T}_{PSrt}, \mathcal{T}_{PEnd}] \leftarrow$ *Extract Time Stamp* $(\mathcal{P}_{Srt}, \mathcal{P}_{End}, \{M_{an}\})$
$[\mathcal{T}_{SSrt}, \mathcal{T}_{SEnd}] \leftarrow$ *Extract Time Stamp* $(\mathcal{S}_{Srt}, \mathcal{S}_{End}, \{M_{an}\})$
for $Count = 1$ to $|P_{Srt}|$ **do**
  for $Tim = \mathcal{T}_{PSrt}(Count)$ to $\mathcal{T}_{PEnd}(Count)$ **do**
    $\{\mathcal{M}_{PCount}\} \leftarrow ExtractMeasurement(\{M\}, \{\tau\}, Tim)$
    $\{\mathcal{M}_{PCount}\} \leftarrow SortAscendOrder(\{M_{PCount}\})$
  end for
end for
for $Count = 1$ to $|S_{Srt}|$ **do**
  for $Tim = \mathcal{T}_{SSrt}(Count)$ to $\mathcal{T}_{SEnd}(Count)$ **do**
    $\{\mathcal{M}_{SCount}\} \leftarrow ExtractMeasurement(\{M\}, \{\tau\}, Tim)$
    $\{\mathcal{M}_{SCount}\} \leftarrow SortAscendOrder(\{M_{SCount}\})$
  end for
end for
for $Count = 1$ to $|P_{Srt}|$ **do**
  $\mathcal{V}alid_{PSpan} \leftarrow M_{PCount}(1) + 180^o$
  $\mathcal{V}alid_{SSpan} \leftarrow M_{SCount}(1) - 180^o$
  $\{\mathcal{V}\ell d_{MPCount}\} \leftarrow ExtractValid(\{M_{PCount}\}, Valid_{PSpan})$
  $\{\mathcal{V}\ell d_{MSCount}\} \leftarrow ExtractValid(\{M_{SCount}\}, Valid_{SSpan})$
  $\{\mathcal{I}n\mathcal{V}\ell d_{MPCount}\} \leftarrow ExtractDiff(\{M_{PCount}\}, \{Vld_{MPCount}\})$
  $\{\mathcal{I}n\mathcal{V}\ell d_{MSCount}\} \leftarrow ExtractDiff(\{M_{SCount}\}, \{Vld_{MSCount}\})$
  $\{\mathcal{M}_{PCount}\} \leftarrow \{Vld_{MPCount}\} \cup \{InVld_{MSCount}\}$
  $\{\mathcal{M}_{SCount}\} \leftarrow \{Vld_{MSCount}\} \cup \{InVld_{MPCount}\}$
end for
$\mathcal{M}^* \leftarrow \{M_{PCount}\} \cup \{M_{SCount}\}$

Error modeling

Errors in measurement, communication, UAV position, environmental disturbances affect localization and its commutative effect can lead to considerable error in localization. For performance analysis, these effects have been modeled and are discussed as follows.

Error due to navigation

The position of each UAV is determined by a satellite-aided inertial navigation system. Cooperative mission employing small UAVs requires aided navigation at all time for a successful mission and navigation error in this scenario depends on accuracy of satellite navigation system, inertial system, and fusion filter characteristics. UAV navigation system is assumed to have a standard deviation of 3 m. The positional error of UAVs is modeled as Gaussian distribution (G) with a standard deviation (σ) of 3 m and it is expressed as $\left(\hat{x}_i, \hat{y}_i\right) = (x_i, y_i) + G(0, \sigma)$ where (x_i, y_i) is the true position of UAV, $\left(\hat{x}_i, \hat{y}_i\right)$ is UAV position determined by its navigation system for ith UAV.

Error due to environment

The terrain and environment conditions affect the acoustic signal propagation due to the presence of reflective and refractive elements.[52] The presence of reflective and refractive elements results in increase and decrease of acoustic pressure, respectively. This effect modifies the acoustic characteristics to a large extent resulting in apparent position shift of source with respect to UAV and is expressed as $\left(\hat{x}_T, \hat{y}_T\right) = (x_T, y_T) + G(0, \sigma)$ where, σ is a standard deviation of 3 m, (x_T, y_T) and $\left(\hat{x}_T, \hat{y}_T\right)$ is the true and apparent position of source respectively. It is assumed that, any position within region of mission interest can be determined with a standard deviation of 3 m.

Error due to measurement

The acoustic sensor is usually mounted in the nose section of the UAV and it often responds to wide band of acoustic signatures. In this paper, it is assumed that the background ego noise is removed[56–62] by signal processing system of the acoustic sensor and filtered sensor output is produced. The error due to mounting, calibration, quantization effects in angle measurement is modeled as Gaussian noise $G(0, \sigma)$ and it is expressed as $\widehat{\theta_i} = \theta_i + G(0, \sigma)$ where, θ_i is a true angle, $\sigma(0.02)$ is a standard deviation in radians.[36]

Similarly, error in range measurement can be expressed as $\hat{d} = d + \mathrm{d}(U_n + G_1) + \alpha G_2$, where d is the true range, U_n is a distance dependent, uniformly distributed, positive error due to non-line of sight, α is the angle between the source and sound source, and G_1 and G_2 are Gaussian noises.[63]

Intra communication link

In a cooperative mission, each UAV shares the information with other UAVs through a communication link, which is modeled as binary number between each pair of UAVs. For a given mission scenario, the presence and absence of link between UAV pairs are modeled as a function of mission time. This effect on localization is negligible when three UAVs are able to intra-communicate with each other.

Error due to communication

In the presence of communication link among UAVs, the delay in transmission and reception of information, presence of noise during transmission, and reception process are modeled, representing the error due to communication. The error is modeled as Gaussian noise $G(0, \sigma)$ and it is expressed as $P_i = p_i + G(0, \sigma)$, where p_i is true engineering value, P_i is communicated value, σ is a standard deviation of 0.02 per unit engineering value.

Mission simulation results on a border surveillance mission scenario

COPSFlyer (CoOPerative System Flyer)

In order to evaluate the integrated performance of localization algorithm (Algorithm to localize synchronized and asynchronized static source emission section), when UAVs following various cooperative trajectories (Cooperative mission trajectory design section), mission simulation for various scenarios was conducted using simulation package *COPSFlyer*. This package has been developed in MATLAB as an interactive visualization and performance evaluation platform and its capabilities include configuration and displaying of vital information of participating elements in various user interface panels.

Two-dimensional UAV trajectories are displayed in mission trajectory panel and each of its characteristics like velocity, mode of operation, status of payload, intra-communication link, and master communication link are displayed in UAV interface panel. Acoustic characteristics (Acoustic source dissipation pattern section) like dissipation pattern, intensity radius, excitation type, time between excitation (discrete), time of appearance, excitation time, and indication of multiple occurrence of sound sources synchronously are displayed in acoustic panel.

Error in measurement, communication, UAV position, environmental, loss in intra-communication, and master control station link are displayed in error characteristics panel. Each UAVs health along with number of healthy UAVs executing cooperative mission is indicated in onboard health monitoring panel. Level of group autonomy (level 5, 6, and 7 in Suresh[64]) along with onboard path planning, decision-making, and trajectory planning functions are displayed in group autonomy panel. Measured value of direction of arrival, estimated and actual source position and its error are displayed in localization panel. This software package has pause and resume provision in addition to mission log panel to log all vital information during mission execution.

Mission scenarios

A cooperative autonomous mission involving four UAVs with the objective to detect and localize acoustic sources is considered. For ease of demonstration of designed algorithm and tactics and explanation of mission sequence, the region of interest is divided into four equal areas (quadrants) of interest. Mission scenarios (Figure 12) are designed depending on acoustic source emission, its appearance in each quadrants, measurements in the presence/absence of error such that appropriate localization algorithm is employed to demonstrate dynamic task assignment, group tactical goal, path replan, and coordination. Similarly, mission scenarios for demonstrating cooperative localization for synchronized sources are shown in Figure 13.

Simulation results

All UAVs are considered as fixed wing aircraft with turn radius constraint and are executing mission at constant altitude. Without loss of generality, all acoustic sources dissipation pattern are considered as monopole. Acoustic source emission type, its time of appearance along with time between excitation is predefined. All algorithms as described in Algorithm to localize synchronized and asynchronized static source emission section are implemented as independent modules and appropriate algorithm is used for a given mission scenario. Errors as described in Error modeling section are used to generate the measured direction of arrival. Euler integration is used to solve differential equations with time step of 10 ms.

Mission simulations have been performed for all the cases as shown in Figure 12. Simulation cases 1–6 correspond to cooperative localization using healthy UAVs. Simulation cases 1, 3, and 5 correspond to single continuous source localization using single UAV employing localization procedure as discussed in COPSFlyer (CoOPerative System Flyer) section. Apart from difference in appearance of source emission among the cases 1, 3, and 5, UAV is restricted to search within its own quadrant in cases 3 and 5. Case 2 corresponds to localization of a discrete source using multiple UAVs employing procedure as described in Simulation results section. The difference between cases 4 and 6 is on appearance of source emission and it corresponds to cooperative source localization using multiple UAVs. Simulation cases 7–9 correspond to localization under failure conditions. For mission performance evaluation studies, case No. 6 (UAVs in healthy condition) and case No. 9 (failure condition) are discussed. Similarly, for synchronous sources as discussed in Figure 13, case No. 2 (UAVs in healthy condition) and case No. 5 (failure condition) are discussed.

1. Multi-UAV multi-Source localization under healthy conditions. Figure 14 shows the snapshot of mission simulation, while executing cooperative mission (case number 6 in Figure 12). It can be seen four UAVs took off from base (rectangular box) and executes group coordination procedures among themselves to reach their designated surveillance area. As indicated in UAV panel, all UAVs are flying at constant velocity of 20 m/s, executing stationing mode (payload in inactive state) with active intra-communication and

Case No.	Scenario	Acoustic source		Localization Algorithm
		Emission	Appearance	
1	UAVs in surveillance in search of sources	Continuous	Random (Sound sources are produced ONLY in one quadrant)	Single UAV Single Source
2	UAVs in surveillance in search of sources	Discrete		Multi UAV Single Source
3	UAVs in surveillance in search of sources (Maintaining keep in zone)	Continuous		Single UAV Single Source
4	UAVs in surveillance in search of sources without zone restrictions	Continuous		Multi UAV Multi Source
5	UAVs in surveillance in search of sources (Maintaining keep in zone)	Continuous	Random (Sound sources are produced in ANY quadrant)	Single UAV Single Source
6	UAVs in surveillance in search of sources without zone restrictions	Continuous		Multi UAV Multi Source
7	UAVs in surveillance in search of sources under failure conditions	Continuous		Multi UAV Multi Source
8	UAVs in surveillance in search of sources under failure conditions	Discrete		Multi UAV Multi Source
9	UAVs in surveillance in search of sources under failure conditions	Continuous and Discrete		Multi UAV Multi Source

Figure 12. Mission scenarios for demonstration of cooperative localization.

Case No.	Scenario	Acoustic source		Localization Algorithm
		Emission	Appearance	
1	UAVs in surveillance in search of sources	Continuous	Random and Synchronous	Multi UAV Multi Source
2		Discrete		
3		Continuous and Discrete		
4	UAVs in surveillance in search of sources under failure conditions	Continuous		
5		Discrete		
6		Continuous and Discrete		

Figure 13. Mission scenarios for demonstration of cooperative localization (synchronous sources).

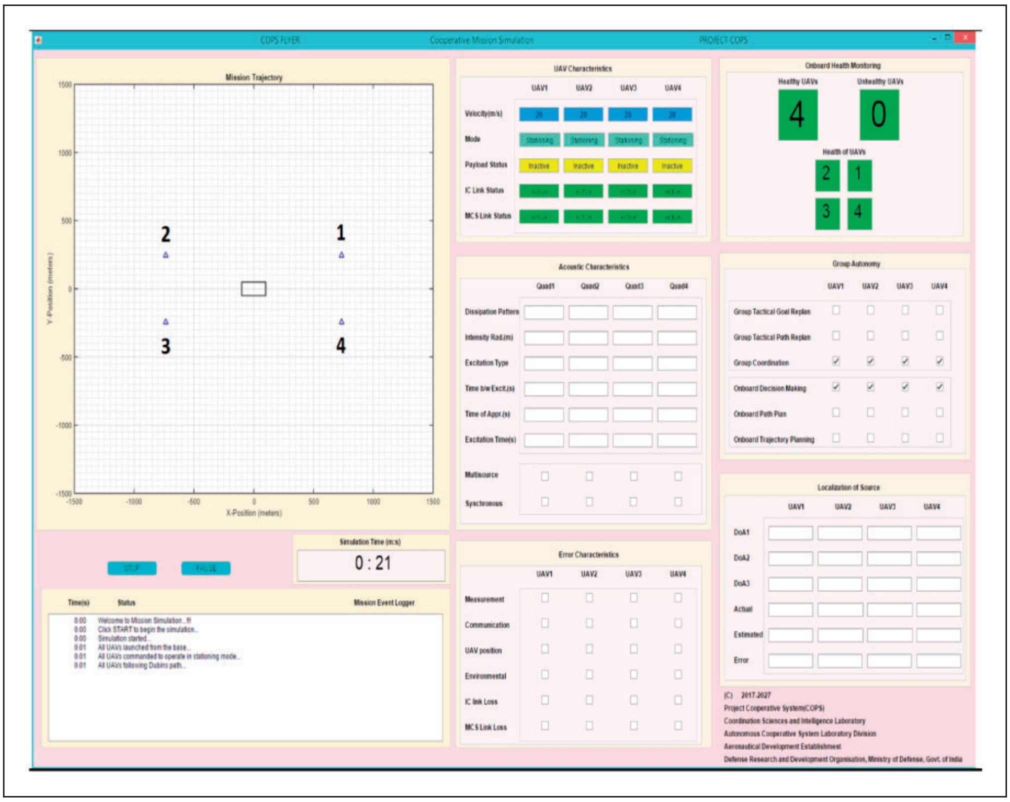

Figure 14. Cooperative mission with healthy UAVs (surveillance mode).

master communication link. As seen in autonomy panel, onboard decision making feature is active, enabling operation modes transition depending on health status (indicated in health panel) and unplanned en route surprise events.

Figure 15 shows the snapshot of mission simulation (trajectory panel) when UAV1 is in surveillance mode seeking for acoustic sources in first quadrant with payload in active state. It can be seen, UAV 2, 3, and 4 are in localization mode with payload in active state. Acoustic sources appeared in second, third, and fourth quadrant are continuous and UAVs upon detection, initiates onboard path and trajectory planning (Dubins path) in order to approach the safe high-intensity radius, to obtain the direction of arrival measurement. In this snapshot (Figure 15), UAV 2 is approaching the safe intensity radius to gather inputs, UAV 3 and 4 completed the localization and in the verge of transition to surveillance mode. The additive of all the errors mentioned in the error panel are added along with actual value calculated based on geometry to represent the measured value of direction of arrival. The measured direction of arrival is indicated both in trajectory panel and displayed in the appropriate text boxes in localization panel. Each UAV, after obtaining three associated measurements pertaining to detected source in its quadrant, localization algorithm is

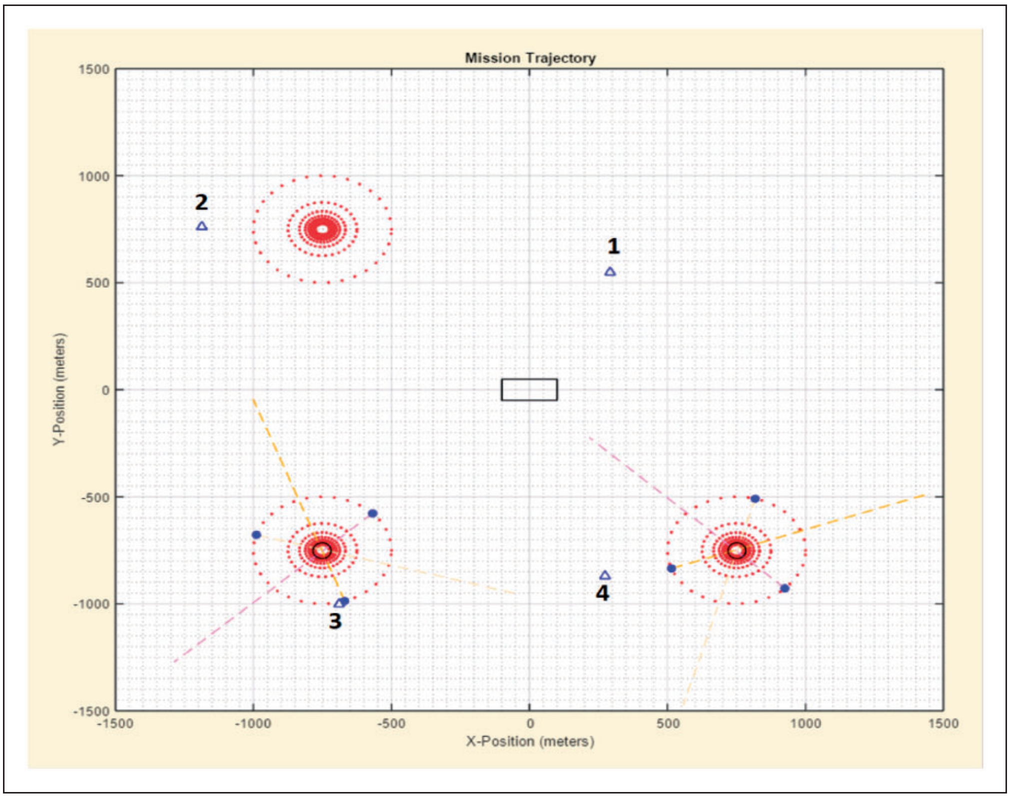

Figure 15. Cooperative mission with healthy UAVs (localization mode).

applied to obtain the estimated source position. The difference between the estimated and actual position of acoustic sources is also displayed as error, whose magnitude depends on the error characteristics.

2. Multi-UAV multi-source localization under healthy conditions. Figure 16 shows the snapshot of mission simulation (trajectory panel), while executing cooperative mission (case number 9 in Figure 12). It can be seen, four UAVs are executing group coordination procedures among themselves in their designated surveillance area. During the mission, UAV 2 detects the failure of its payload. Upon detection, UAV 2, communicates its payload inactive status to rest of team members, commands itself to *back to home* mode that initiates onboard path and trajectory plan (Dubins path) to reach the base, from its current position.

After failure of UAV 2, continuous acoustic source was detected by UAV 3 in quadrant 3. Upon detection, UAV 3 initiates onboard path and trajectory generation (Dubins path) to reach the safe intensity radius for localization. Meanwhile, discrete acoustic source is detected by UAV 4 in its quadrant. As the source is discrete, UAV 4 transmits message to all UAVs, seeking cooperation. UAV 3 declined as it is in the process of localizing continuous source. UAV 1 extends its cooperation and started flying towards UAV 4, but discrete sound source is detected in its own quadrant. Then, UAV 1 transmits message to all UAVs seeking cooperation. As localization is not complete by UAV 3, it declines. Both UAV 4 and UAV 3 agree to cooperate between themselves and initiate group tactical path and goal replan. Onboard path and trajectory algorithm generate a race course pattern[64] as shown in Figure 17. Both the UAVs follows the trajectory, measures the direction of arrival from both discrete sources. After obtaining three associated direction of arrival values pertaining to each source, localization algorithm is applied to localize the acoustic source, as shown in localization panel. After localization of discrete source, UAV 4 and 1 return to the original surveillance area, while UAV 3 follows a race course pattern covering both second and third quadrants.

3. Multi-UAV multi synchronized source localization under healthy conditions. Figure 18 shows the snapshot of mission simulation (trajectory panel), while executing cooperative mission (case number 2 in Figure 13). It can be seen, four UAVs are executing group coordination procedures among themselves in the entire surveillance area. UAVs sensing and communication range are assumed to cover the entire surveillance area. It can also be seen that three discrete acoustic sources are appearing for a short duration of 1 s (as shown in acoustic panel), with their safe intensity radius covering the entire surveillance area. At the time of acoustic source occurrence, all UAVs measure the direction of arrival of all acoustic sources, which is displayed in localization panel.

All the measured direction of arrival with embedded error characteristics is applied to the

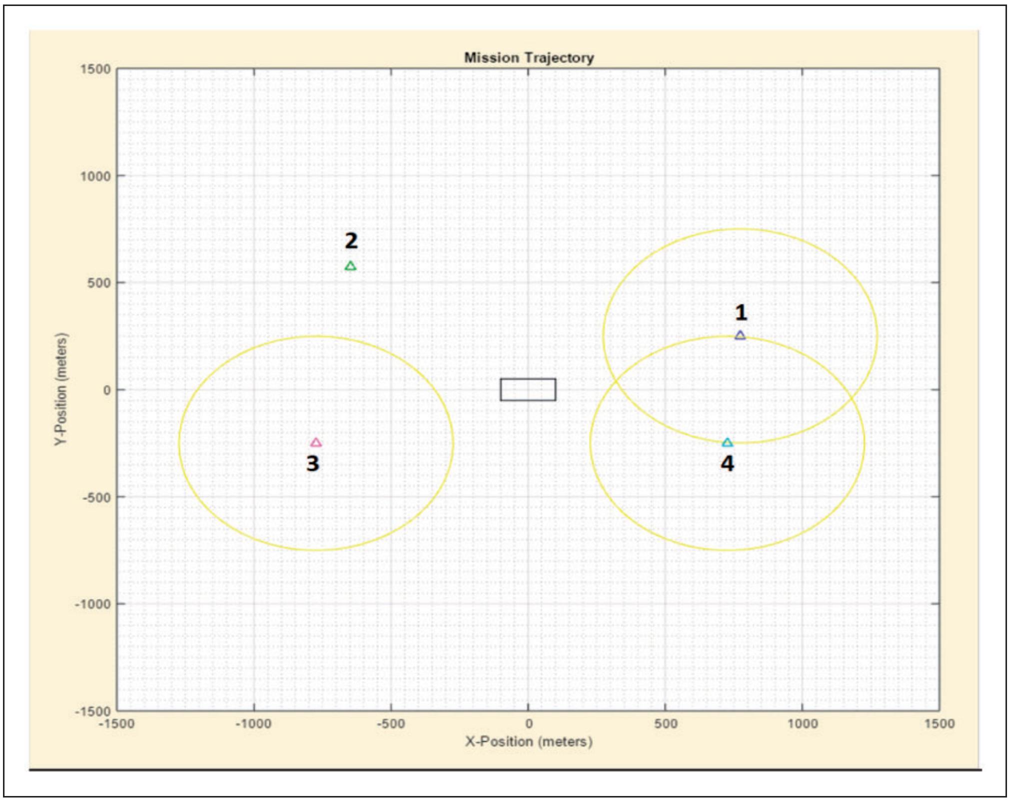

Figure 16. Cooperative mission under failure condition (back-to-home mode).

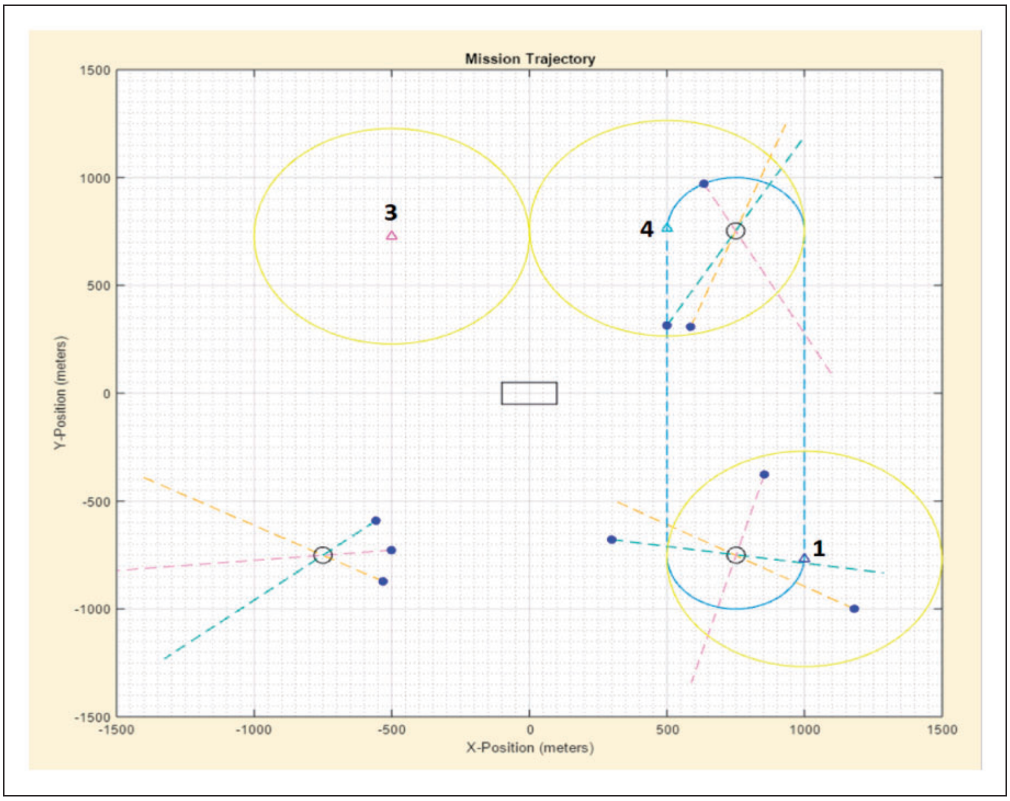

Figure 17. Cooperative mission under failure condition (localization mode).

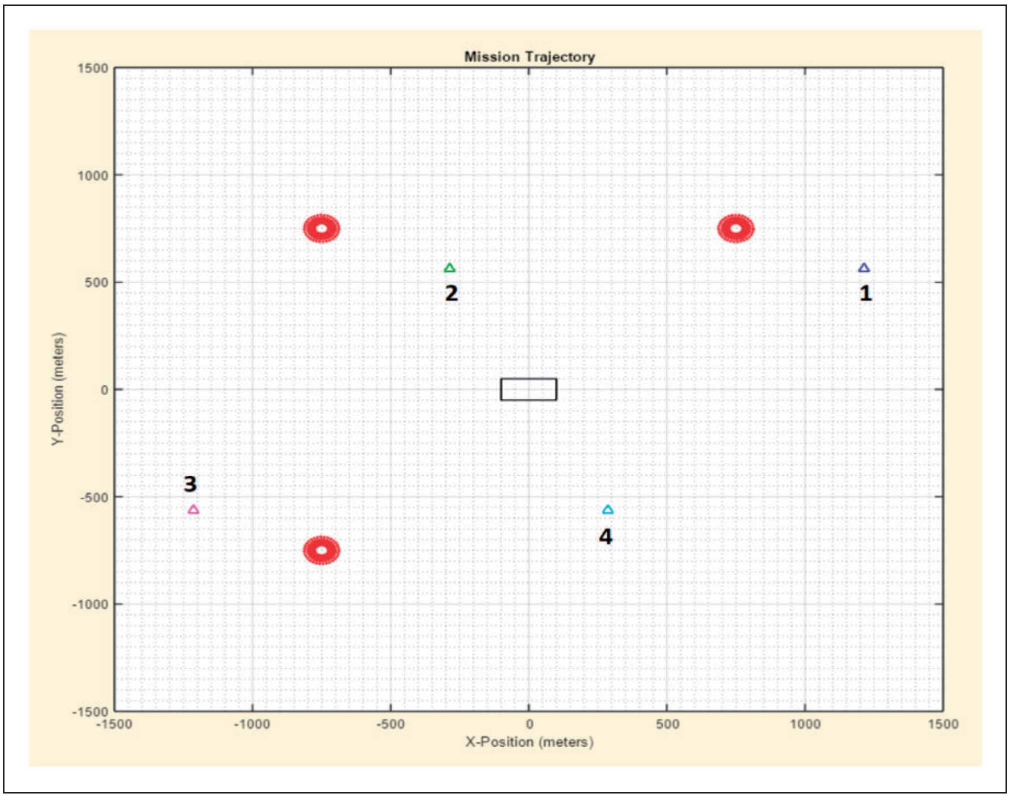

Figure 18. Cooperative mission to localize multi-synchronized source under healthy condition (discrete source emission).

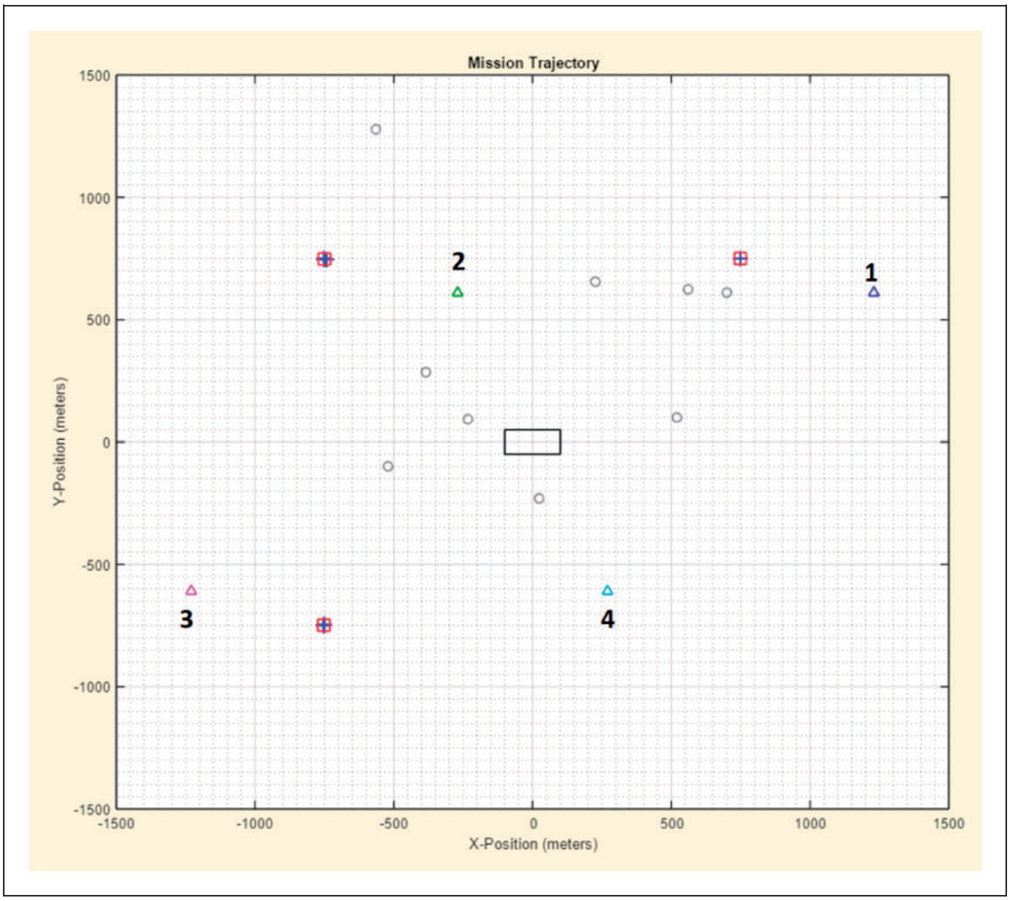

Figure 19. Cooperative mission to localize multi-synchronized source under healthy condition (localization mode).

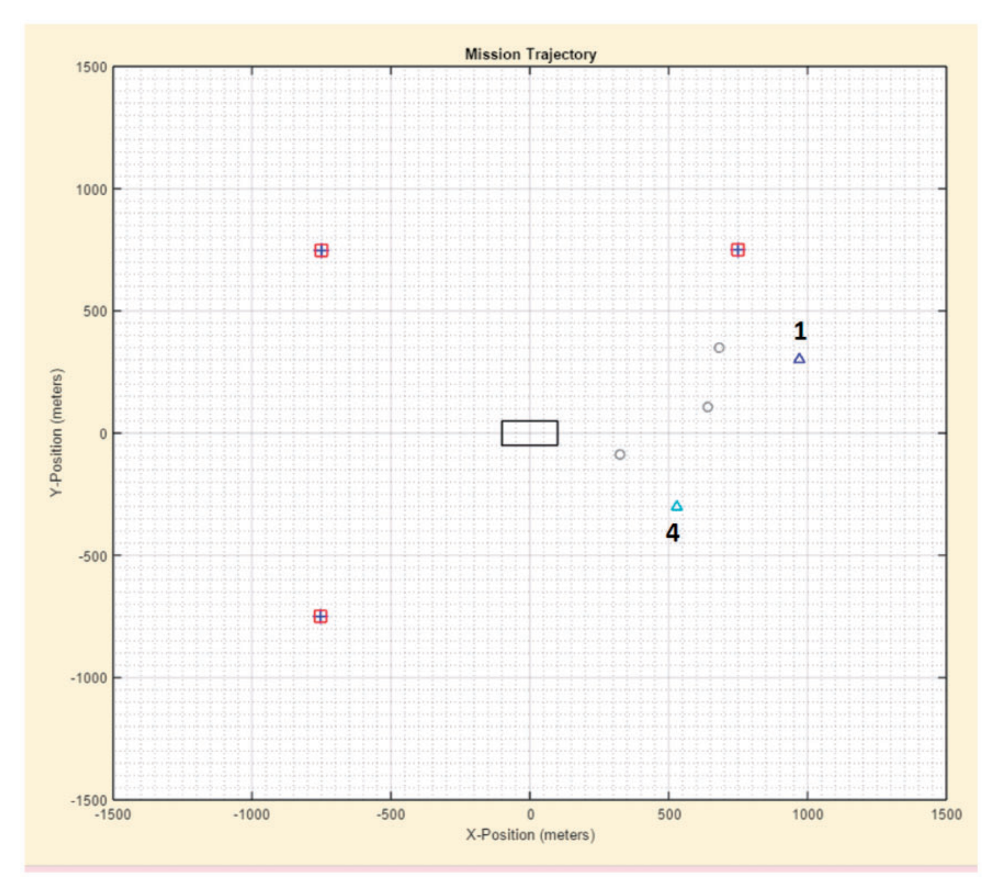

Figure 20. Cooperative mission to localize multi-synchronized source under failure condition (localization mode).

localization algorithm to determine the intersection points and the ghost nodes. The intersection and ghost nodes are indicated in the trajectory panel (Figure 19) as plus (+) and unfilled circle (o) respectively. Number of intersection and ghost nodes is also displayed in the localization panel. After applying ghost node elimination, localization algorithm estimates the acoustic sources position (indicated as square in trajectory panel) and displayed in localization panel along with error from the actual position.

4. Multi-UAV multi-synchronized source localization under failure conditions. Figure 20 shows the snapshot of mission simulation (trajectory panel), while executing cooperative mission (case number 5 in Figure 13). In this case, UAVs 2 and 3 are assumed to be failed (as indicated in UAV panel) and hence there are no measurements from them. Onboard path and trajectory planning are not initiated by UAVs 1 and 4, as its sensing radius is assumed to cover the entire surveillance area. Based on the measured direction of arrival from three sources, the intersection points and ghost nodes are shown in localization panel. After elimination of ghost nodes, the localization algorithm estimates the source position which is displayed in localization panel along with actual position and error.

The above mission simulation results demonstrate the effectiveness of designed cooperative localization algorithm performance even under UAV failures in the presence of all error conditions.

Conclusions

This paper presents an end-to-end solution for multi-UAV multi-acoustic source localization in a dynamic contested environment. Existing single and multi-source localization methods are revisited and new contributions like MAP localization method and ghost node elimination techniques for synchronized multiple sources are presented. Both single and multi-source localization algorithms were evaluated in different mission scenarios to arrive at a ready reference for implementation. NP hardness in determining minimum number of UAVs satisfying localizability criteria was shown and heuristic solution is proposed. Cooperative mission trajectory for different scenarios was designed and snake trajectory is proved as optimal to provide maximum coverage for a specific source configuration. Errors in measurement, navigation, and communication are modeled and mission simulation was performed using MATLAB-based COPSFlyer software package. Cooperative mission simulation under nominal and off-nominal conditions is simulated to demonstrate the efficiency of the developed algorithms in presence of realistic error conditions.

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