Decentralized Formation of UAVs with UWB-Based Bias Correction

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Abstract. The study proposes a formation restoring algorithm (FRA) designed to enhance the accurate formation of multiple unmanned aerial vehicles (UAVs), particularly under conditions of significant GPS inaccuracies. The proposed algorithm utilizes ultra-wideband (UWB) modules for high-precision distance measurements between UAVs, enabling the detection and correction of formation shape distortions in a decentralized manner. The core of the FRA is the computation of a restoring vector, representing the real position required for each UAV to adjust its position back to the intended formation shape. To estimate both the current position of each UAV and the required restoring vector, the algorithm handles a equality constraints through Kalman filter, representing the accurate distances between UAVs, as measured by the UWB modules. This method ensures that adjustments to UAV positions are both minimal and precise, significantly improving formation fidelity under conditions where GPS is unreliable. The effectiveness of the FRA has been validated through numerical simulations and experiments, demonstrating its capability to maintain tight formation control and significantly reduce the impact of GPS bias on formation flight.

Keywords: Position bias error, Sensor fusion, Ultra-Wideband(UWB).

1 Introduction

UAV formation flight requires precise control of relative positions; however, performance significantly drops when GPS errors occur. GPS accuracy is highly sensitive to environmental factors, such as tropospheric refraction, geomagnetic disturbances, and multipath interference, each causing substantial positioning errors. For example, tropospheric refraction leads to signal delays that increase at lower elevation angles, particularly impacting distance accuracy[1]. Likewise, geomagnetic disturbances, often triggered by solar activity, disrupt ionospheric electron density and cause positional inaccuracies, especially affecting single-frequency receivers[2]. Additionally, multipath interference, where GPS signals reflect off nearby surfaces, results in phase shifts that further degrade positional accuracy and are challenging to correct with conventional methods[3].

To address these errors, Ultra-Wideband (UWB) sensors are used to measure relative distances between UAVs, enabling the correction of GPS signal inaccuracies. UWB is a wireless communication technology operating across a broad frequency range, providing high-precision, short-range distance measurements. This accuracy makes UWB particularly effective in environments where GPS signals may be unreliable or unavailable. While LiDAR and cameras offer alternative solutions, their effectiveness is limited by high costs and sensitivity to environmental conditions[4-6], making UWB a lightweight and efficient option. Recent studies have demonstrated that combining UWB with odometry-based relative localization (RL) techniques can maintain stable UAV formations even in GPS-denied environments, showing robust performance under challenging conditions[7].

This paper proposes the Formation Restoring Algorithm (FRA), which combines GPS and UWB data to reduce GPS errors. The FRA calculates a restoring vector based on UWB measurements to precisely align the UAVs' relative positions, reducing formation errors and improving control accuracy.

2 Methodology

2.1 Formation Structural Error

The formation structural error is a numerical indicator representing the difference between the actual shape of the UAV formation and the desired shape. When the relative distances between UAVs match the target distances, the error becomes zero. This error is defined as follows:

$$e_f = \frac{1}{N(N-1)} \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \left| \left\| \boldsymbol{\rho}_f^{(ij)} \right\| - \left\| \boldsymbol{\rho}_g^{(ij)} \right\| \right| \tag{1}$$

- e_f : formation structural error.
- $\boldsymbol{\rho}_f^{(ij)}$: desired relative position between UAV i-th and UAV j-th
- $\boldsymbol{\rho}_g^{(ij)}$: actual relative position between UAV i-th and UAV j-th

2.2 Sensor Fusion for Formation Restoring Algorithm

To minimize the formation structural error, constraints are set to ensure the relative distances between UAVs match the desired distances. Ideally, the desired relative position $\boldsymbol{\rho}_f^{(ij)}$ equals the actual relative position $\boldsymbol{\rho}_g^{(ij)}$, making the error zero:

$$\left\| \boldsymbol{\rho}_f^{(ij)} \right\| - \left\| \boldsymbol{\rho}_g^{(ij)} \right\| = 0 \tag{2}$$

Since the position $\boldsymbol{\rho}$ contains bias errors, a restoring vector $\mathbf{r}$ is introduced, with the corrected position given by:

$$\boldsymbol{\rho}_f = \boldsymbol{\rho} + \boldsymbol{r}, \qquad \left\| \boldsymbol{\rho}_g \right\| = d \tag{3}$$

The actual relative distance $\|\boldsymbol{\rho}_g\|$ is measured by the UWB sensor, assumed to be a perfect measurement. Thus, the equality constraint to minimize the error becomes:

$$\left\| \boldsymbol{\rho}^{(ij)} + \boldsymbol{r}^{(ij)} \right\| - d^{(ij)} = 0 \tag{4}$$

The FRA is implemented using an Extended Kalman Filter (EKF) to iteratively reduce formation errors. In this EKF, the **state vector** consists of the position estimate with bias $\boldsymbol{\rho}$ and the restoring vector $\mathbf{r}$, which corrects this bias. The observation vector incorporates both GPS and UWB data to estimate relative positions. GPS provides position information but includes bias, while UWB serves as an accurate reference measurement, helping to align the formation structure accurately.
Within the Kalman filter's prediction step, the state vector is updated based on previous estimate. The state prediction is represented as:

$$\widehat{\boldsymbol{X}}_{\boldsymbol{k}|\boldsymbol{k}-\mathbf{1}} = \boldsymbol{F}\widehat{\boldsymbol{X}}_{\boldsymbol{k}-\mathbf{1}|\boldsymbol{k}-\mathbf{1}} \tag{5}$$

where $\boldsymbol{X}$ is the combined state vector of $\boldsymbol{\rho}$ and $\mathbf{r}$, and $\boldsymbol{F}$ is the identity matrix, allowing the state to be propagated without changing its inherent values. The covariance matrix is updated as:

$$\boldsymbol{P}_{\boldsymbol{k}|\boldsymbol{k}-\mathbf{1}} = \boldsymbol{F}\boldsymbol{P}_{\boldsymbol{k}-\mathbf{1}|\boldsymbol{k}-\mathbf{1}}\boldsymbol{F}^{\boldsymbol{T}} + \boldsymbol{Q} \tag{6}$$

where $\mathbf{Q}$ represents process noise, tuned to account for environmental variability and model uncertainties.
In the correction step, the filter applies three key adjustments to refine the state estimate. First, GPS measurements are used to correct $\boldsymbol{\rho}$, providing an updated biased position. Second assuming that the GPS bias error follows a Gaussian distribution with a mean of zero, a pseudo-measurement is introduced to keep the restoring vector $\mathbf{r}$ close to zero, thereby minimizing the bias. Finally, a constraint is applied to ensure consistency between the state estimate and accurate reference distances. This constraint is enforced as:

$$\|\boldsymbol{\rho} + \boldsymbol{r}\| - d = 0 \tag{7}$$

This aligns the combined position and restoring vector with the UWB data *d*, which is assumed to be a perfect measurement. The observation noise covariance matrix $\mathbf{R}$ is also tuned to reflect the accuracy of these measurements, enabling the filter to weigh each correction step appropriately based on the level of detected bias.

3 Simulation

Sensor characteristics for numerical simulation are listed in Table 1. The simulation is based on several assumptions: the network has no packet drops or delays, sensors deliver data with no latency and at a precise sampling rate, and UAVs start from random initial positions and orientations. This randomized setup allows for evaluation of the algorithm's robustness in establishing formation from diverse starting conditions.

Table 1. Sensor Characteristics for the Simulation

Sensors	Specifications	Value
GPS	Update rate	10 Hz
	Fixed bias error variance	[1 m, 1 m, 2 m]
	Variance	0.03 m
UWB	Update rate	3.5 Hz
	Variance	0.008 m

Fig. 1 shows a simulation of the FRA. The algorithm corrects the GPS-biased initial positions using restoring vectors, guiding the UAVs towards their target positions. The blue lines represent the UAVs' adjusted trajectories after applying the algorithm. Although the UAVs do not reach the exact target points, the formation maintains a stable triangular shape.

Fig. 2(a) shows how the relative distances between UAVs converge over time, reducing formation structural error. Fig. 2(b) shows the distance between each UAV and its target, indicating that while UAVs approach the target, they don't achieve perfect convergence.

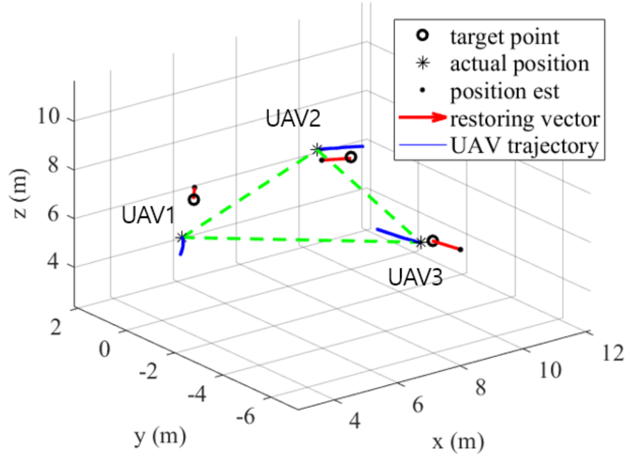
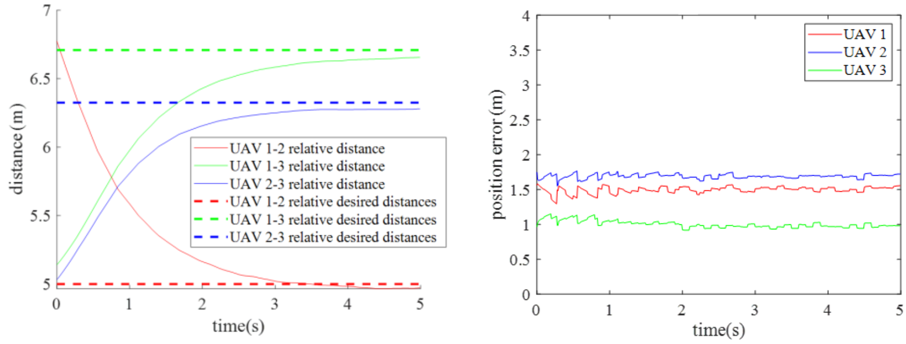


Fig. 1. Numerical simulation result.



(a) (b)

Fig. 2. (a) Convergence of Relative Distance Errors between UAVs, (b) Position Error between UAVs and Target Points

The simulation results show that the FRA is effective in correcting GPS bias and maintaining UAV formation. In Fig. 2(a), it can be observed that the relative distance error converges correctly, indicating that the formation structure error has been effectively reduced and that the formation is well-established. However, Fig. 2(b) shows that the UAVs did not reach their target points. This is because maintaining the formation does not guarantee that each UAV will reach its absolute target position. Maintaining the formation and achieving perfect convergence to each UAV's target position are separate issues, and further improvements are necessary to address this.

4 Conclusion

This paper proposed the effectiveness in the formation of UAVs through the FRA, even in the presence of GPS bias. The FRA successfully reduced relative distance errors and maintained the structural integrity of the formation. While the relative distances converged to the target values, the results indicated that further adjustments may be necessary to achieve complete convergence to the absolute target points.

In future research, the focus will be on improving the algorithm to ensure that each UAV can reach its precise target position while maintaining the formation. Specifically, addressing issues such as translational and rotational drift of the formation will be key. Additionally, dilution of precision(DOP) will be employed to enhance the accuracy of the algorithm and ensure more robust formation control. The ultimate goal is to develop a more reliable solution that guarantees both formation accuracy and target convergence in real-world UAV applications.

Acknowledgements. This research was financially supported by the Korea AeroSpace Administration (KASA) through the Helicopter Electric Multiple Tail Rotor Technology R&D program, in part by the National Research Foundation of Korea grant funded by the Korea government (MSIT) under Grant 2020R1A6A1A03040570, and in part by the Regional Innovation Mega Project program through the Korea Innovation Foundation funded by the Ministry of Science and ICT under Grant 2023-DD-UP-0026.

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