# Cooperative Drift Mitigation for UAV Swarms in GNSS-Denied Environments

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## 1. Introduction

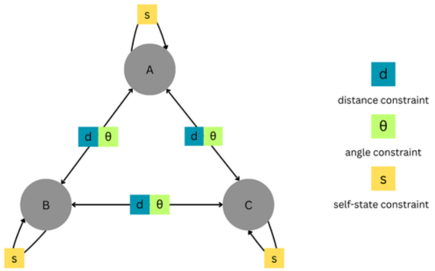
- **The Problem**: In GNSS-denied areas, UAVs rely on onboard inertial sensors, leading to severe, compounding error accumulation (inertial drift).
- **Our Objective**: Leverage cooperative estimation within UAV swarms to cross-reference spatial uncertainties and bound absolute trajectory drift.

## 2. Existing Approaches

| **Method** | **Mechanism** | **Advantage** | **Disadvantage** |
|---|---|---|---|
| **Basic Dead Reckoning (DR)** | Onboard Sensor Data | Easy implementation | Susceptible to unbound drift |
| **Sensor Fusion (EKF)** | Blends Data from Multiple Streams | Bounds drift effectively | Requires complex mathematical modeling |
| **AI-based Approaches** | Machine Learning Predictions | Handles non-linear noise | Fails in unfamiliar environments |
| **Cooperative EKF** | Shares Data across Swarm | Bounds drift | Communication bottlenecks at scale |
| **Distributed Graph Optimization (DGO)** | Models Swarm as Graph | Scalable | (Addressed in research) |

## 3. System Design

- **Sensor Models:** Onboard sensors measure relative distance, angle, and self-state displacement.
- **Decentralized Execution**: Drones solve localized optimization subproblems in parallel and broadcast computed positions to neighbors.
- **The Core Modification (Normalization)**: Standard DGO biases towards swarm cohesion as swarm size increases. We introduce a normalized composite objective function to balance this cohesion with absolute positioning.

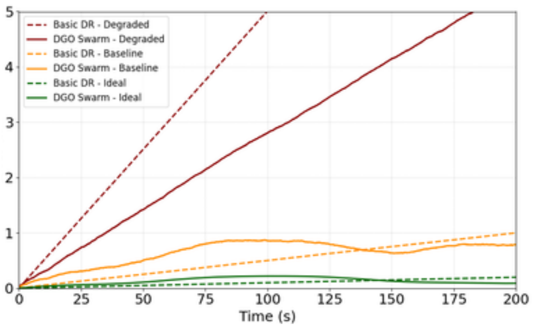


- $J_i^d(k)$ **(Distance Cost)**: Penalizes deviations from measured geometric distances.
- $J_i^\theta(k)$ **(Angle Cost)**: Minimizes discrepancies in camera bearing measurements.
- $J_i^s(k)$ **(State Cost)**: Minimizes drifting IMU measurements.

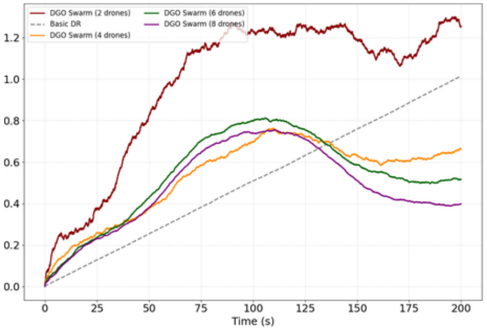
$$\hat{\mathbf{p}}_i(k) = \arg\min_{\mathbf{p}_i(k)} \left( \frac{1}{|\mathcal{D}_i|} J_i^d(k) + \frac{1}{|\Theta_i|} J_i^\theta(k) + J_i^s(k) \right)$$

**Optimized Position Estimation**

## 4. Experiments and Results



**DGO outperforms Basic DR under low quality sensors**



**Increasing Swarm Size Increases Efficiency**

## 5. Conclusion and Future Work

- **Trade-off:** While DGO incurs a minor short-term accuracy penalty due to sensor variance, it achieves superior stability over prolonged missions.
- **Control Integration:** Future work will reintegrate the Distributed Model Predictive Control (DMPC) module.
- **Complex Kinematics:** The simulation environment should be expanded to evaluate variable UAV kinematics, including different flight speeds and Y-axis positions.