Onboard Ranging-based Relative Localization and Stability for Lightweight Aerial Swarms

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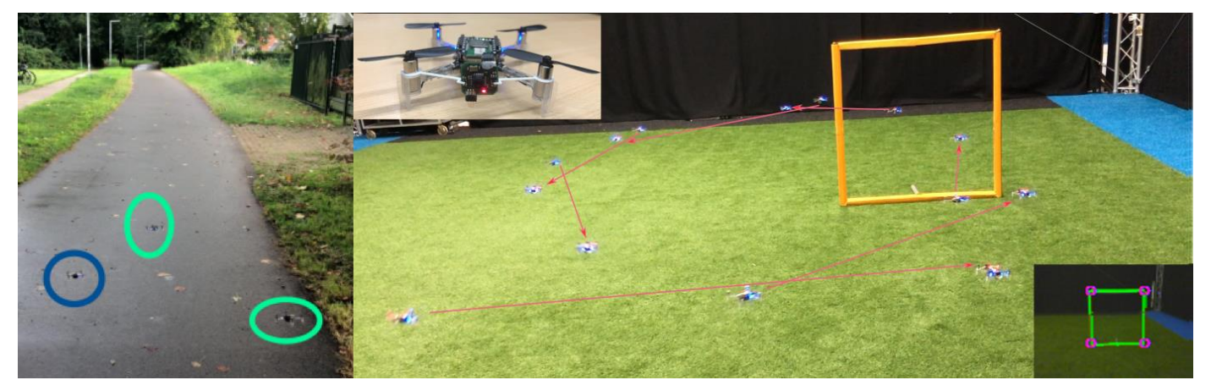
1. Key Contributions

- First fully autonomous onboard relative localization on 13 lightweight aerial vehicles (33 g, 168 MHz MCU, 192 KB memory).
- UWB swarm ranging supports simultaneous communication and ranging without infrastructure.
- Self-regulated convergence: unobservable formation states become observable again through drift and control actions.
- Open-source implementation for off-the-shelf Crazyflie quadrotors.

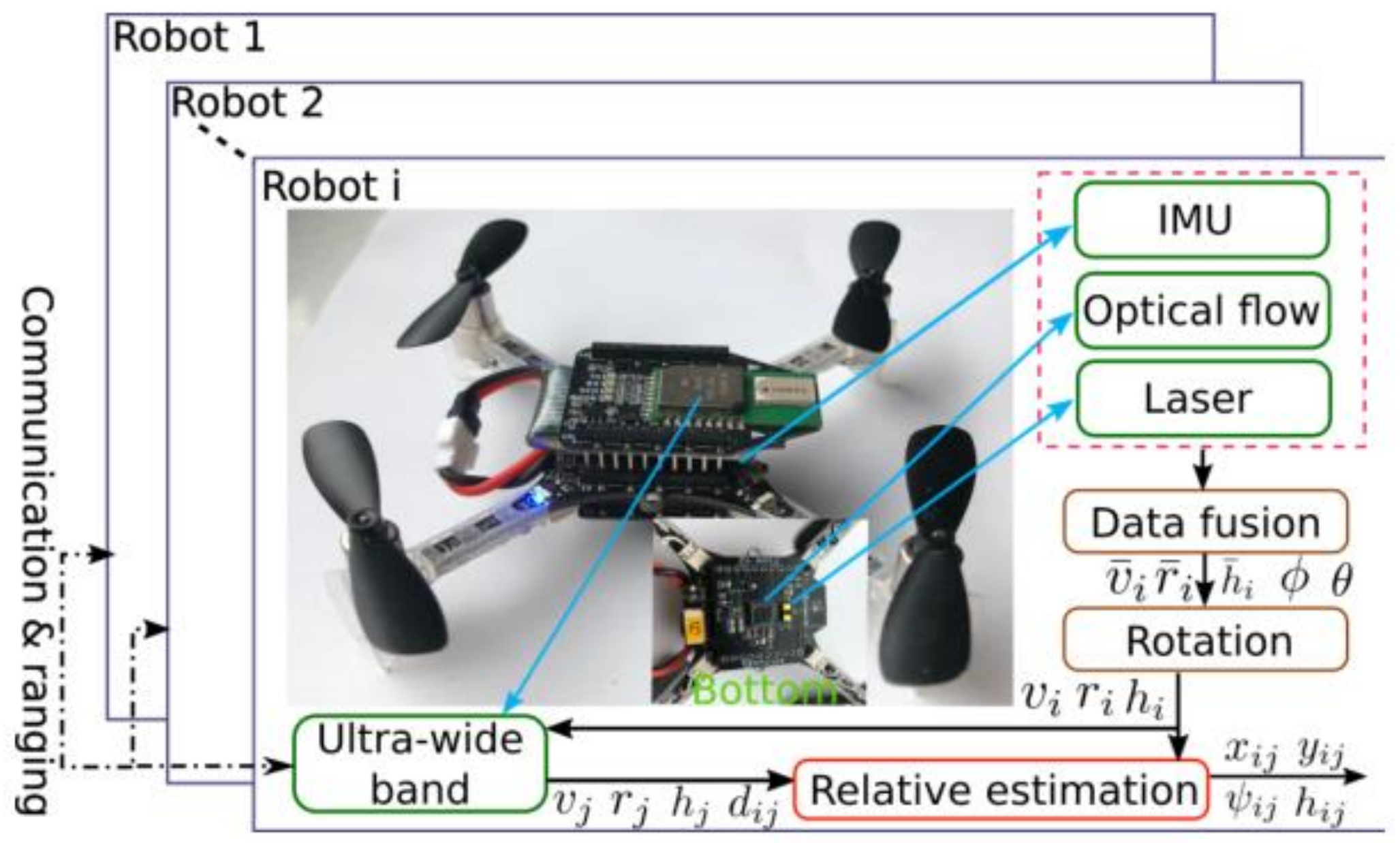
Tiny + Onboard + Scalable



Outdoor formation flight & indoor leader follower flight

Video & code

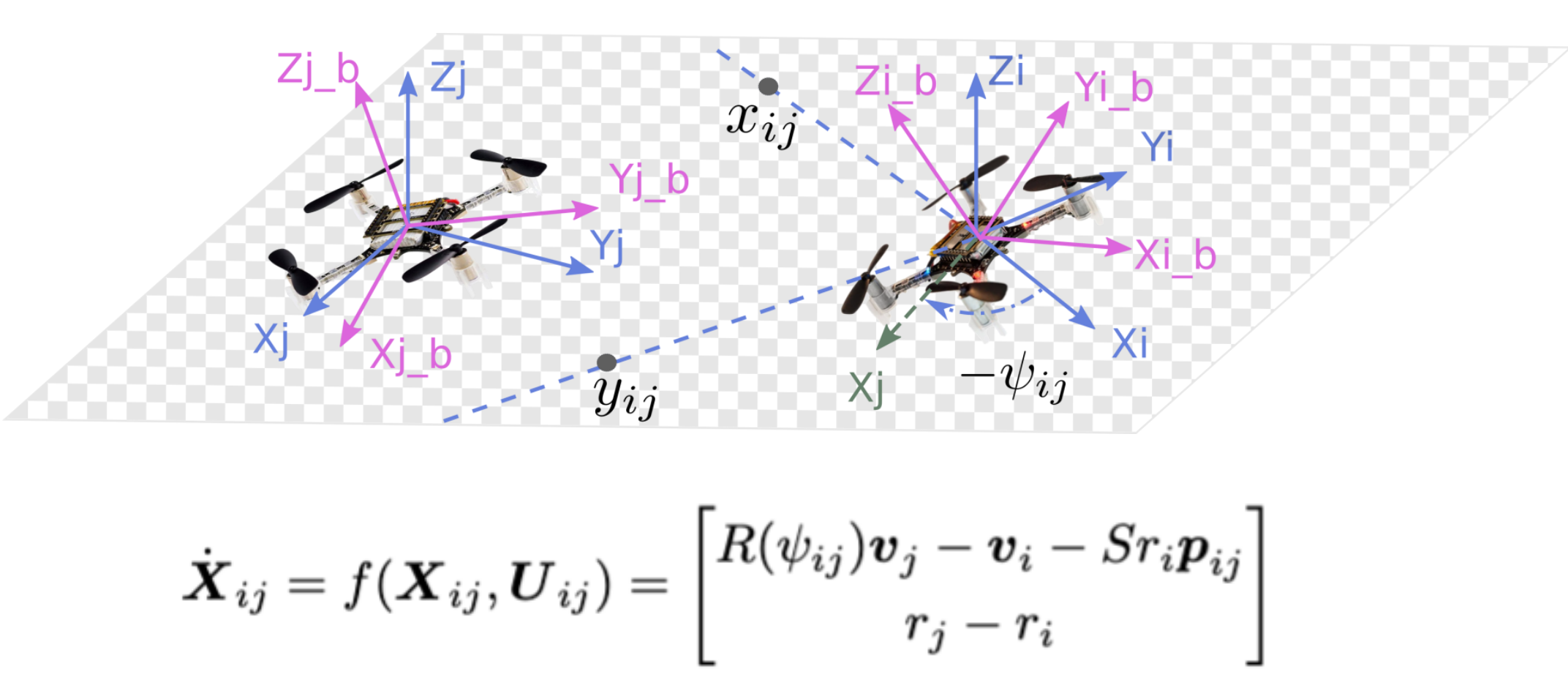
2. System Overview



Onboard sensing + UWB communication and ranging

Pipeline

- Sensors: IMU, optical flow, laser height, UWB.
- Shared state: velocity, yaw rate, height.
- Output: ego-centered relative pose $X_{ij} = [x_{ij}, y_{ij}, \psi_{ij}]^T$.
- Estimator runs fully onboard on resource-constrained MCU.



$$\dot{\boldsymbol{X}}_{ij} = f(\boldsymbol{X}_{ij}, \boldsymbol{U}_{ij}) = \begin{bmatrix} R(\psi_{ij})\boldsymbol{v}_j - \boldsymbol{v}_i - S r_i \boldsymbol{p}_{ij} \\ r_j - r_i \end{bmatrix}$$

Relative kinematic model

16 Hz
Ranging/localization frequency

13-robot
swarm in real world

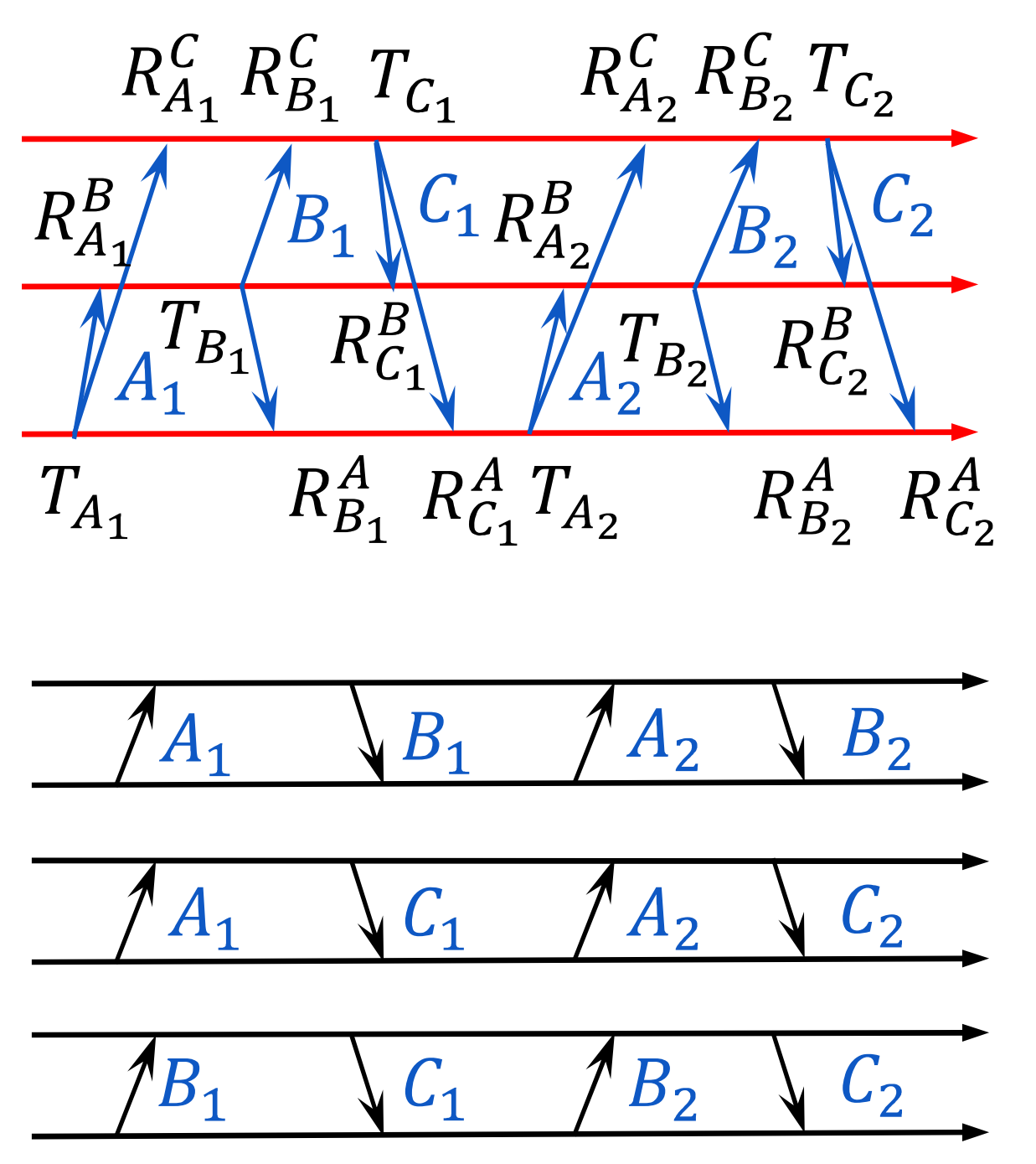
<0.2 m
Position error

33 g
Drone mass

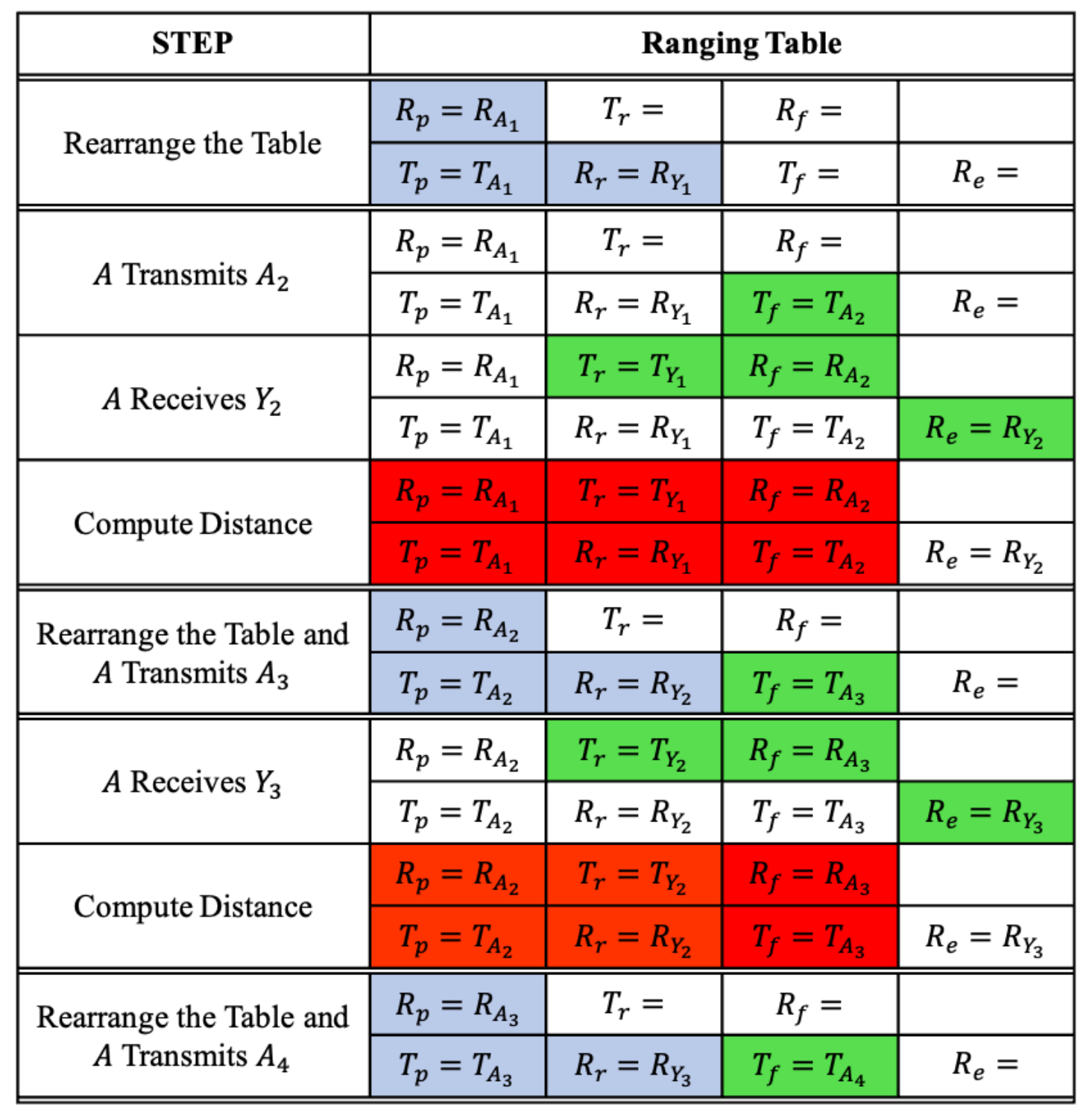
192 KB
MCU memory

3. Method: UWB Swarm Ranging + Tiny EKF

Ranging protocol



An illustration of the swarm ranging protocol



STEP	Ranging Table			
Rearrange the Table	$R_p = R_{A_1}$	$T_r =$	$R_f =$	
	$T_p = T_{A_1}$	$R_r = R_{Y_1}$	$T_f =$	$R_e =$
A Transmits A_2	$R_p = R_{A_1}$	$T_r =$	$R_f =$	
	$T_p = T_{A_1}$	$R_r = R_{Y_1}$	$T_f = T_{A_2}$	$R_e =$
A Receives Y_2	$R_p = R_{A_1}$	$T_r = T_{Y_1}$	$R_f = R_{A_2}$	
	$T_p = T_{A_1}$	$R_r = R_{Y_1}$	$T_f = T_{A_2}$	$R_e = R_{Y_2}$
Compute Distance	$R_p = R_{A_1}$	$T_r = T_{Y_1}$	$R_f = R_{A_2}$	
	$T_p = T_{A_1}$	$R_r = R_{Y_1}$	$T_f = T_{A_2}$	$R_e = R_{Y_2}$
Rearrange the Table and *A* Transmits A_3	$R_p = R_{A_2}$	$T_r =$	$R_f =$	
	$T_p = T_{A_2}$	$R_r = R_{Y_2}$	$T_f = T_{A_3}$	$R_e =$
A Receives Y_3	$R_p = R_{A_2}$	$T_r = T_{Y_2}$	$R_f = R_{A_3}$	
	$T_p = T_{A_2}$	$R_r = R_{Y_2}$	$T_f = T_{A_3}$	$R_e = R_{Y_3}$
Compute Distance	$R_p = R_{A_2}$	$T_r = T_{Y_2}$	$R_f = R_{A_3}$	
	$T_p = T_{A_2}$	$R_r = R_{Y_2}$	$T_f = T_{A_3}$	$R_e = R_{Y_3}$
Rearrange the Table and *A* Transmits A_4	$R_p = R_{A_3}$	$T_r =$	$R_f =$	
	$T_p = T_{A_3}$	$R_r = R_{Y_3}$	$T_f = T_{A_4}$	$R_e =$

Swarm ranging steps

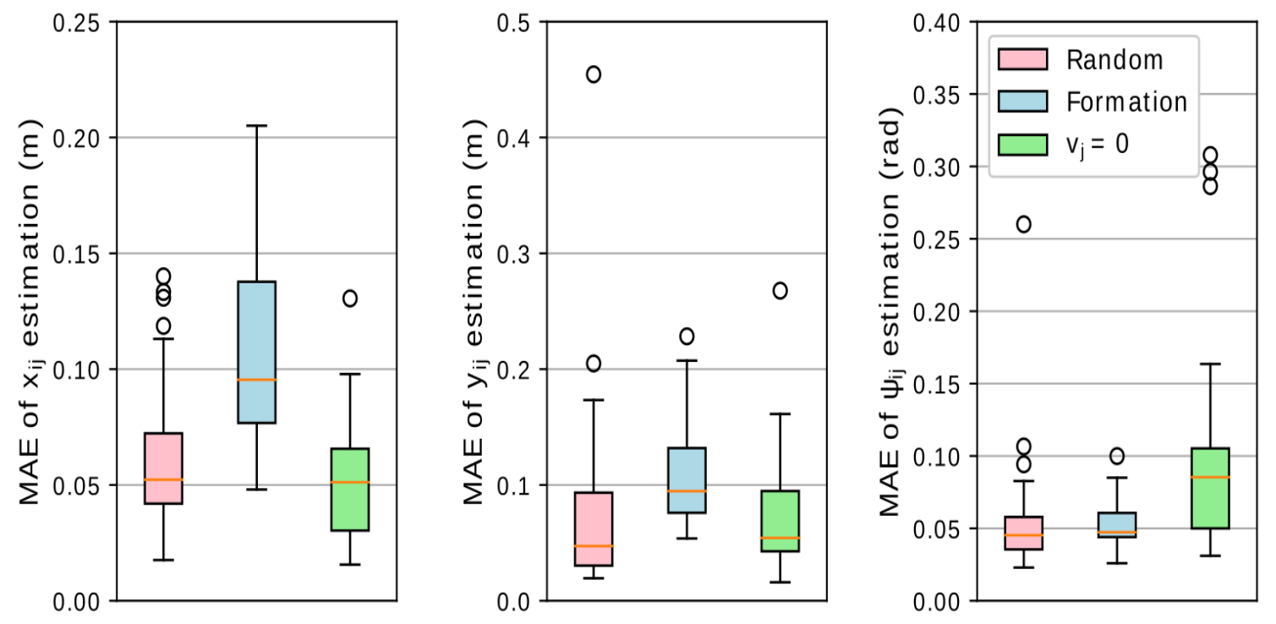
- One broadcast ranging message, not pairwise token passing.
- Each packet carries sender ID, sequence number, transmit timestamp, neighbor reception timestamps, velocity, yaw rate and height.
- Six timestamps recover ToF; a per-neighbor ranging table keeps the state compact.

Relative localization

Type of data	Data of message		
Onboard Sensing Data	*Message Identification*		
	Flight Velocity v_i	*Yaw Rate r_i*	*Flight Height h_i*
	Last transmission Timestamp T_i		
Ranging Data for Neighbor 1	*Sequence Number*	*Reception Timestamp R_i^1*	
...	...		
Ranging Data for Neighbor N	*Sequence Number*	*Reception Timestamp R_i^N*	

The proposed ranging message that supports relative localization.

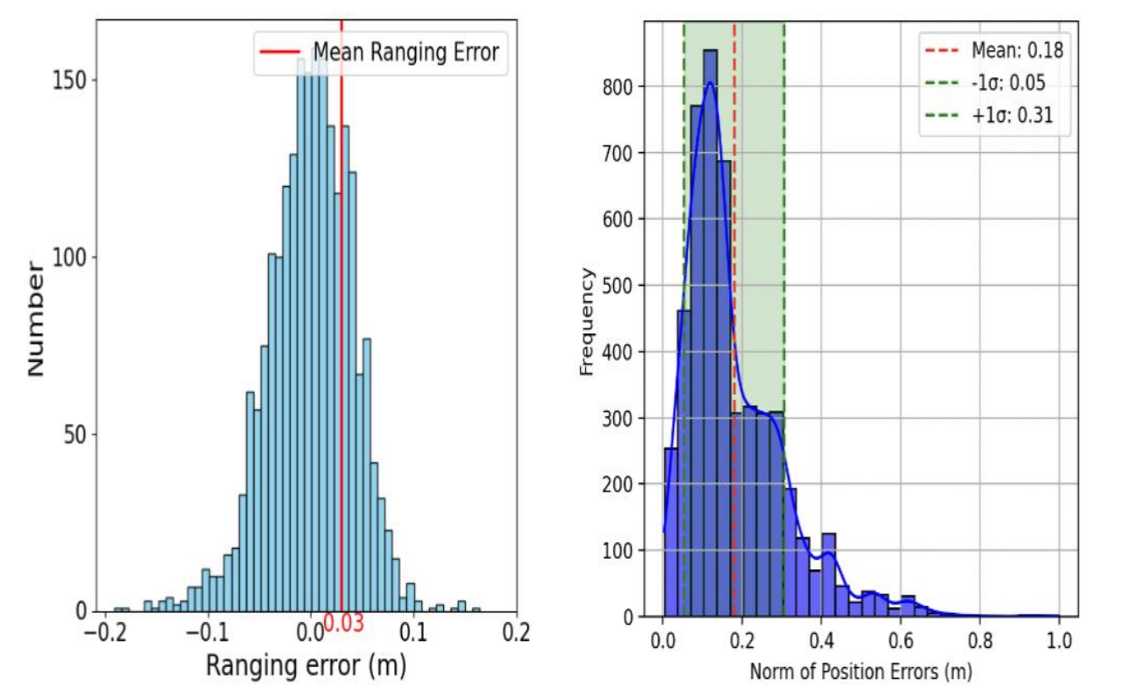
- EKF is selected for low compute overhead.
- Prediction: relative kinematics driven by both robots' velocities and yaw rates.
- Update: UWB range $z = \sqrt{x^2 + y^2 + \Delta h^2}$.
- Stochastic initialization removes the need for manual initial relative poses.



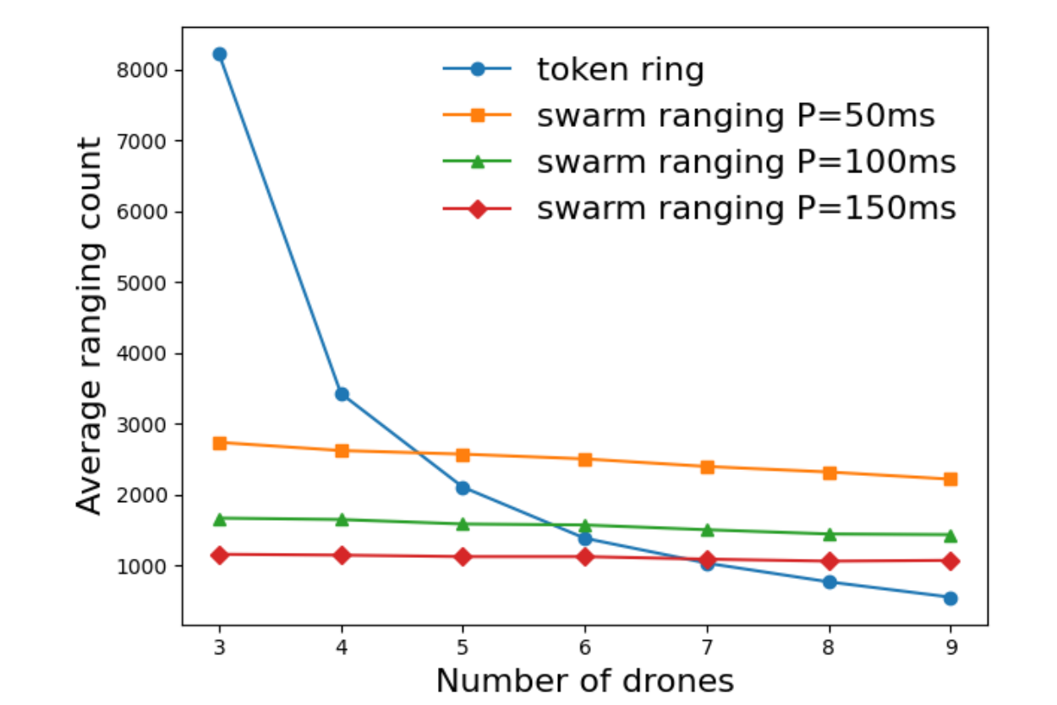
Error distribution of relative localization in different unobservable situations.

Theoretical result: formation flight can be locally unobservable, but estimation drift triggers control corrections that restore observability.

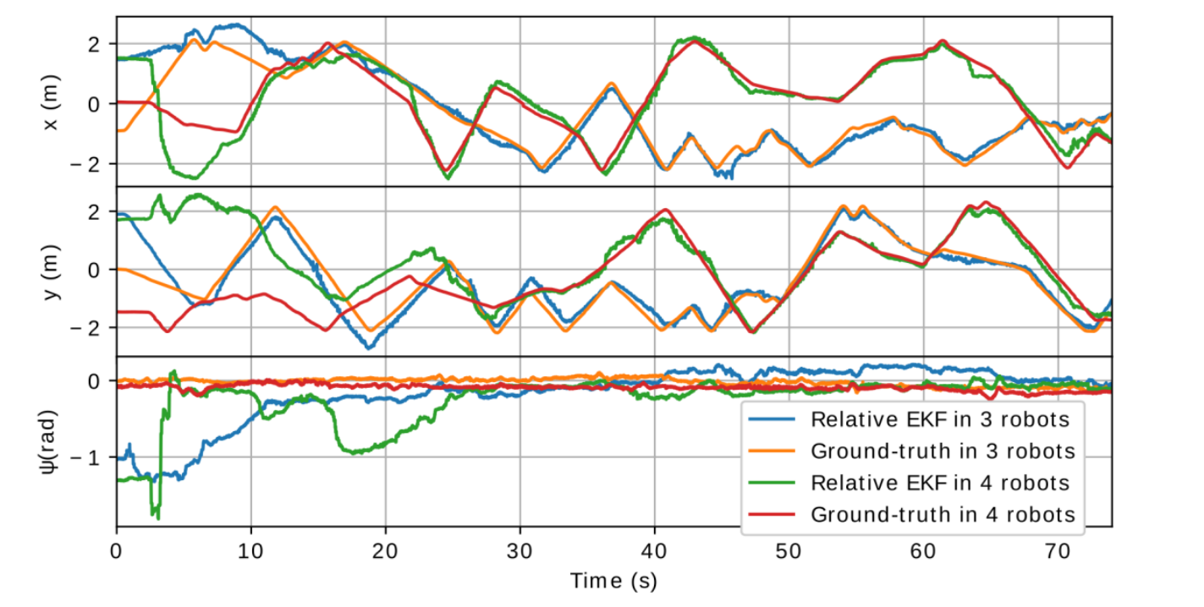
4. Real-world Experimental Results



UWB measurements and position norm error distribution



Comparison with ranging based on token ring



3-dimensional localization error

0.03 m
mean UWB ranging error

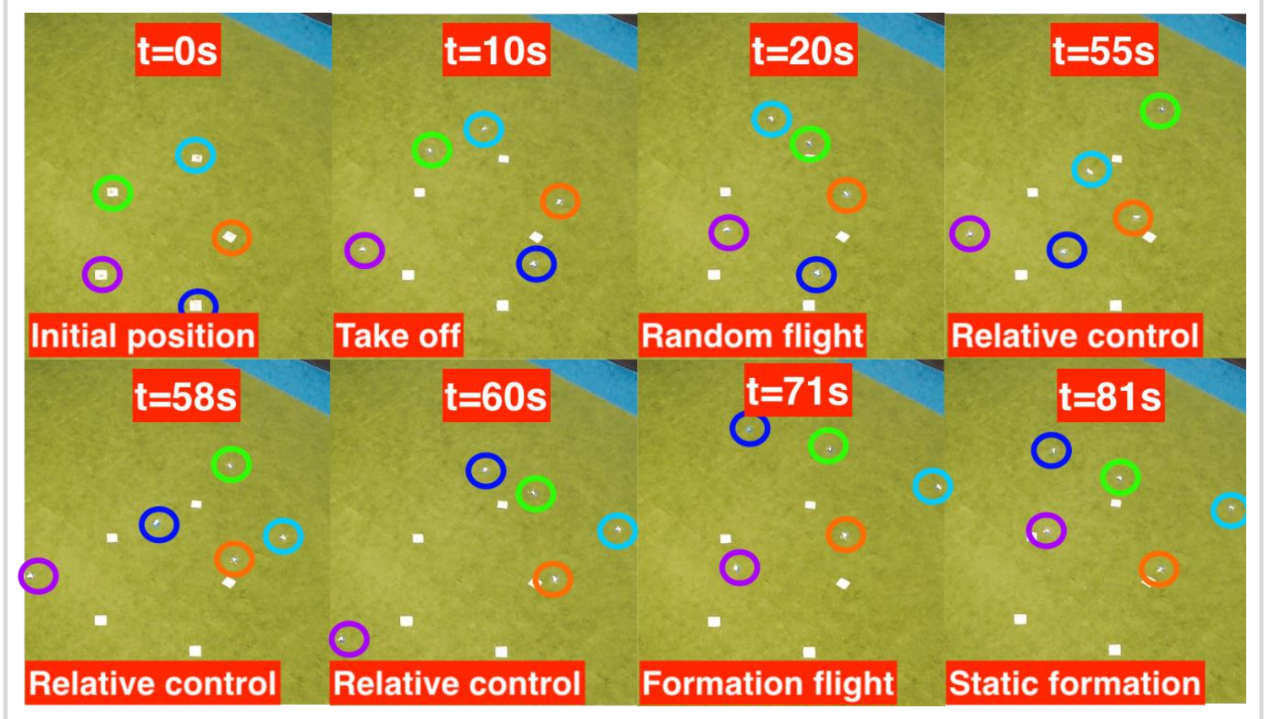
~80%
packet reception with >20 drones

0.662 ms
processing delay, 26 drones

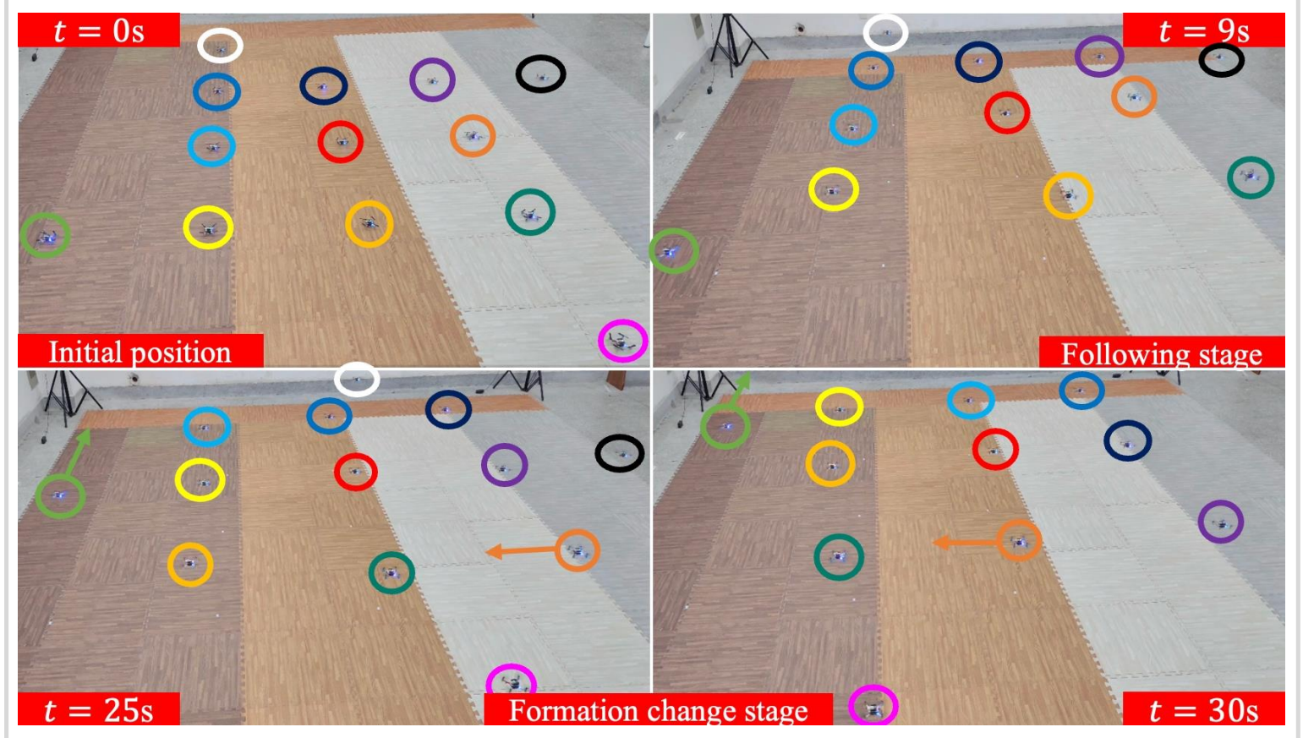
~0.13 m
relative localization

Method	Dependence				Accuracy and Number
	IMU	Velocity	Height	North	
2019, [21]	●	●	●	●	40Hz, ∼0.2m, 3
2020, [20]	●	●	●		16Hz, ∼0.22m, 3
2020, [22]	●	●	●	●	10Hz, ∼1.4m, 2
2021, [23]	●			●	10Hz, ∼0.6m, 2
Ours	●	●	●		**16Hz, ∼0.13m**, 13

Comparisons with the state-of-the-art UWB relative localization methods



Top view of the formation flight of 5 robots



Top view of the formation flight of 13 robots.

- Outperforms token-ring ranging as swar m size grows.
- Initial states converge in about 20 s in real flights.
- 5-drone and 13-drone formation flights validate closed-loop use of onboard localization.

Results use OptiTrack only for ground-truth validation; localization and control run onboard.