PhD Open Days

Long-Term Cooperative Sparse LiDAR and Inertial Relative Localization for GNSS-Denied Multi-UAV Teams

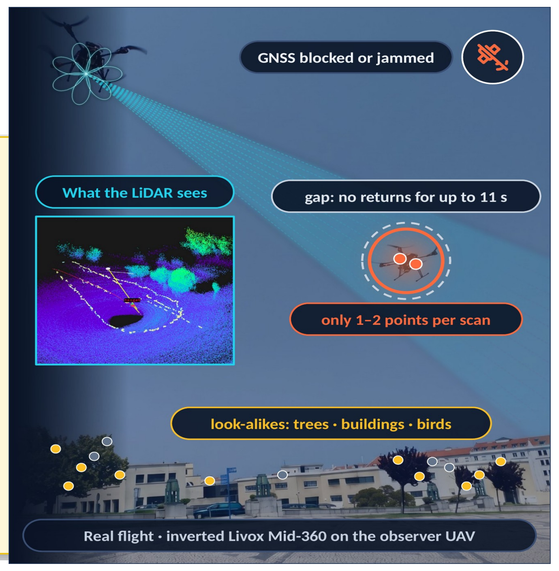
Institute for Systems and Robotics | LISBOA

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Why it matters

When GNSS fails, a team of drones must still know where every teammate is.

Research question How can a multi-UAV team reliably detect its members from sparse, cluttered LiDAR returns, and maintain an accurate and consistent relative-state estimate over long horizons when these detections are intermittent and delayed?



1 Research challenges and progression toward cooperative localization

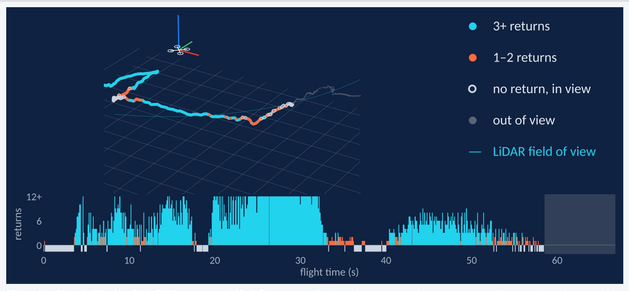


Fig. 1 · Real flight D1-F5*: *every LiDAR scan of the observer; the teammate's path coloured by its returns.*

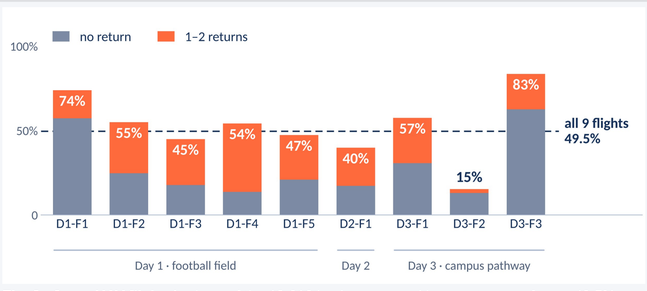


Fig. 2 · 9 two-UAV flights*: *share of the 12,616 in-view scans with two returns or fewer: 49.5% overall, 27% with none.*

1 · Sparse LiDAR detection [2] — PUBLISHED · ICMRE 2026
Half of the in-view scans give two returns or fewer (Fig. 2). Range-adaptive clustering and temporal checks detected a UAV from one or two returns, but only inside a predefined search region.

2 · Semi-cooperative relative localization [3] — PUBLISHED · ICARSC 2026
With these sparse detections, the inertial measurements of both UAVs kept relative position and velocity through outages of up to 11 s: 64% lower relative-position RMSE than constant-velocity prediction.

3 · SPARC: observation-supported detection — CURRENT RESEARCH
No predefined search region: candidates are ranked by local context, recorded-ray support and range-conditioned return counts, with temporal association; nine two-UAV flights, 16 observer runs.

4 · Integrated long-term localization — ONGOING INTEGRATION
Combining SPARC with cooperative estimation, under delayed measurements, ambiguous associations and weakly observable relative motion.

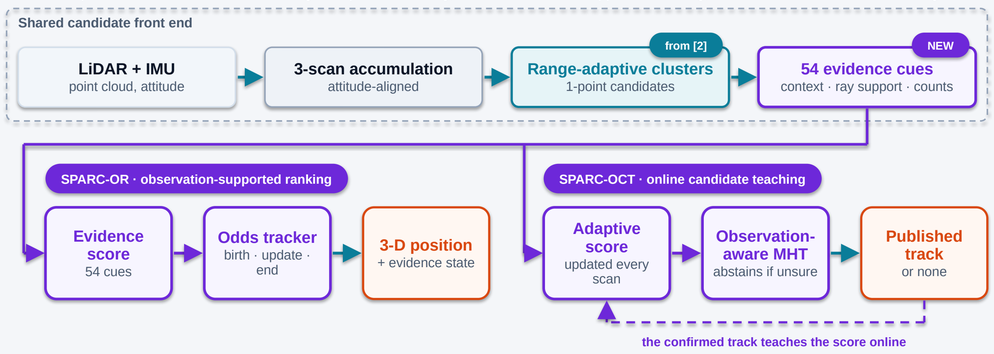
2 Approach · C1 detection and C2 cooperative estimation

C1 · SPARC: evidence-based detection from 1–2 points

Extension[2]

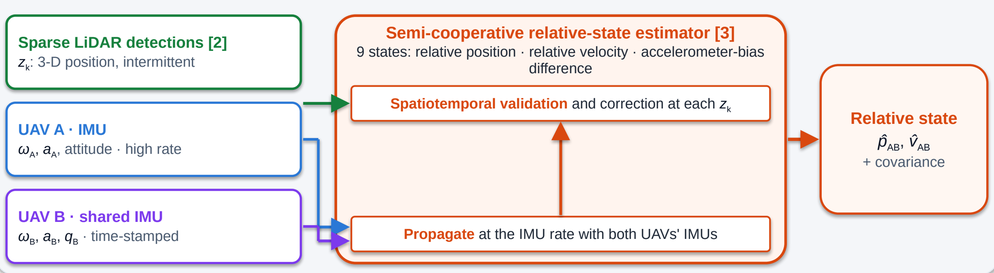
Why SPARC can tell a UAV from clutter: it checks whether recorded LiDAR rays actually traversed the space around each candidate, and whether occupied structure (a branch, a wall) is attached to it; unobserved regions are never treated as empty.

SPARC = *Sparse Point Accumulation and Range-adaptive Clustering;* **OR** = *Observation-supported Ranking;* **OCT** = *Online Candidate Teaching.*



C2 · Semi-cooperative dual-IMU relative localization

IEEE ICARSC 2026 [3]



3 Results · C1: SPARC in real two-UAV flights

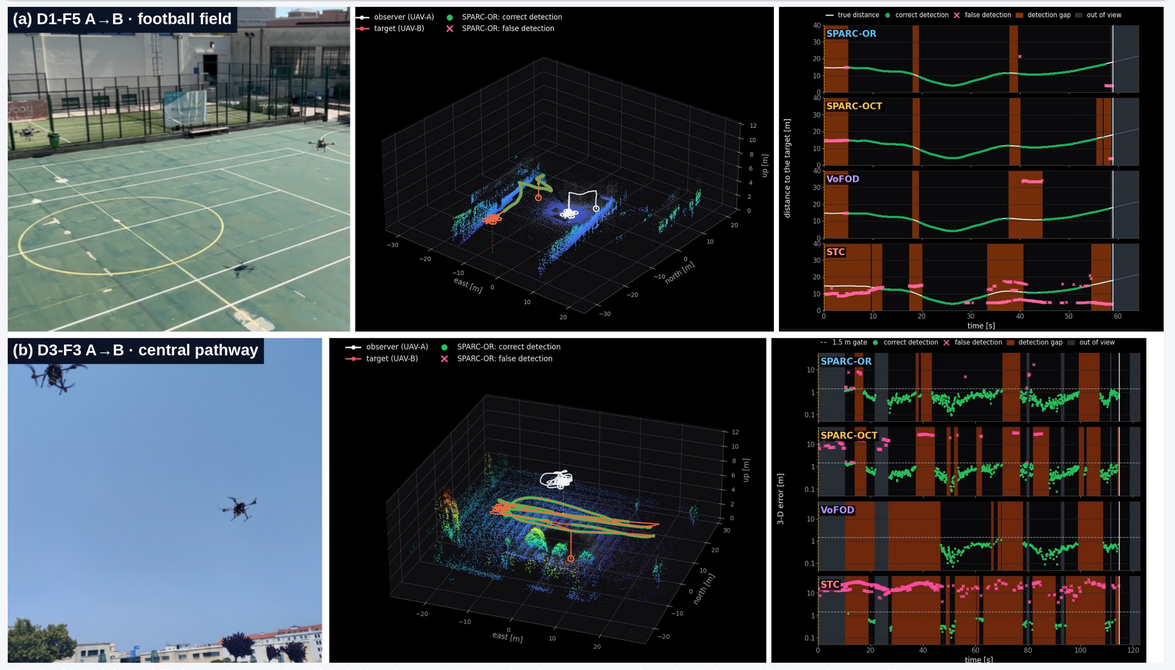


Fig. 3 · SPARC in real flights*: *site, complete flight in the observer's LiDAR view (green: correct detections), four methods on the same flight.*

87.1%	median F1 (VoFOD [4]: 73.5%)
81.8%	recall (VoFOD: 65.0%)
281 s	missed in view (VoFOD: 469 s)
> 90%	F1 on a different LiDAR (Ouster)

Nine two-UAV flights comprising 16 observer runs (3 days, 2 sites)*: SPARC has the higher F1 on 14 of the 16 runs, by a median of 12.7 points.

4 Results · C2: shared inertial measurements in real flights

IEEE ICARSC 2026 [3]

−64% relative-position error (1.43 vs 3.96 m)	**−65%** relative-velocity error (0.61 vs 1.75 m/s)	**11 s** longest gap bridged, 13 outdoor segments

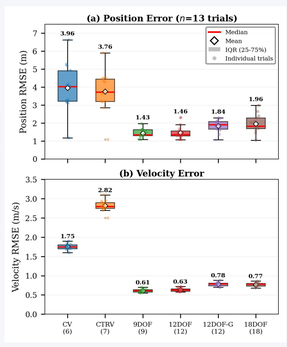


Fig. 4 · [3]: *RMSE over 13 segments, CV/CTRV vs 9- to 18-state filters*



Fig. 5 · Experiment [3]: *the GNSS-denied test site and the observer's sparse LiDAR view.*

Shared IMUs beat both motion models; the 9-state filter is the most accurate (1.43 m, 0.61 m/s); the 12- and 18-state variants do not improve on it.

5 Toward integrated, uncertainty-aware cooperative localization

- **Detection from one or two LiDAR points:** SPARC reaches a median F1 of 87.1% over 16 observer runs (strongest baseline [4]: 73.5%).
- **Estimation through observation gaps:** shared inertial measurements cut the relative-position error by 64% and the relative-velocity error by 65%, over gaps of up to 11 s [3].

Next stage: detection and estimation integrated in one cooperative localization framework

- **Relative attitude** — the estimated relative state extended to include attitude
- **Temporal consistency** — consistent estimates under delayed, multi-rate measurements
- **Estimation feedback** — the prediction strengthens candidate association and re-detection
- **Observability and experiments** — observability analysis and extended multi-UAV experiments

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[2] N. Khosravi, R. Ventura, M. Basiri, "Unsupervised LiDAR-based multi-UAV detection and tracking under extreme sparsity with comparative data association analysis," ICMRE 2026, pp. 330–336, doi:10.1109/ICMRE69538.2026.11533899.
[3] N. Khosravi, R. Ventura, M. Basiri, "Semi-cooperative dual-IMU relative localization for UAV-to-UAV tracking with sparse 3D LiDAR detections," IEEE ICARSC 2026, pp. 175–181, doi:10.1109/ICARSC70216.2026.11523287.
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[5] F. Zhu, Y. Ren, L. Yin, F. Kong, Q. Liu, R. Xue, W. Liu, Y. Cai, G. Lu, H. Li, F. Zhang, "Swarm-LIO2: decentralized efficient LiDAR-inertial odometry for aerial swarm systems," IEEE Trans. Robot., vol. 41, pp. 960–981, 2025, doi:10.1109/TRO.2024.3522155.
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** Current research, not yet published: SPARC and the 9-flight dataset (football field and the central pathway of the Técnico campus, RTK/DGPS reference).*

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