10th International conference on Control, Automation, and Diagnosis
Lisbon, Portugal, July 7-9, 2026

Energy-Aware Control Optimization Strategies for Multimodal Collaborative Robotic Platforms

Pawan Kumar[1], Jueming Hu[2], Gail-Joon Ahn[1], and Hokeun Kim[1]

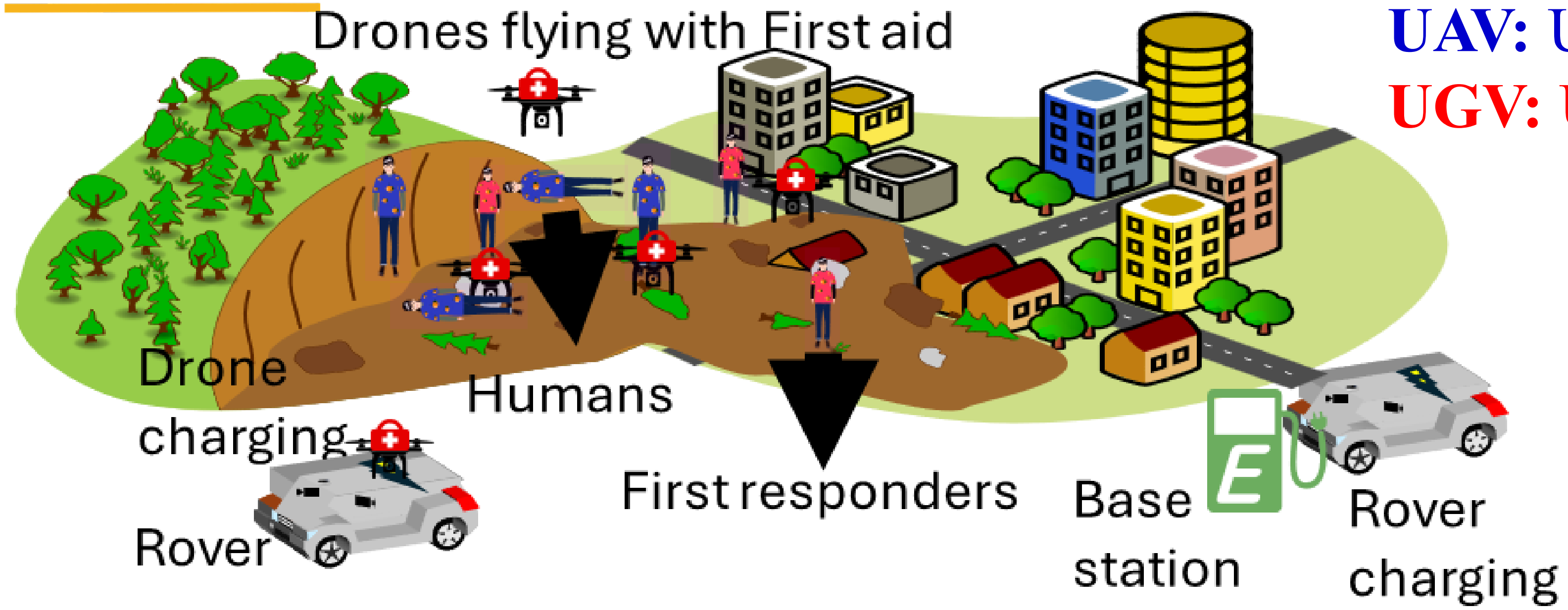
[1] Arizona State University
[2] University of North Dakota

Presenter: Pawan Kumar

https://www.iccad-conf.com/

PLAN

Motivation



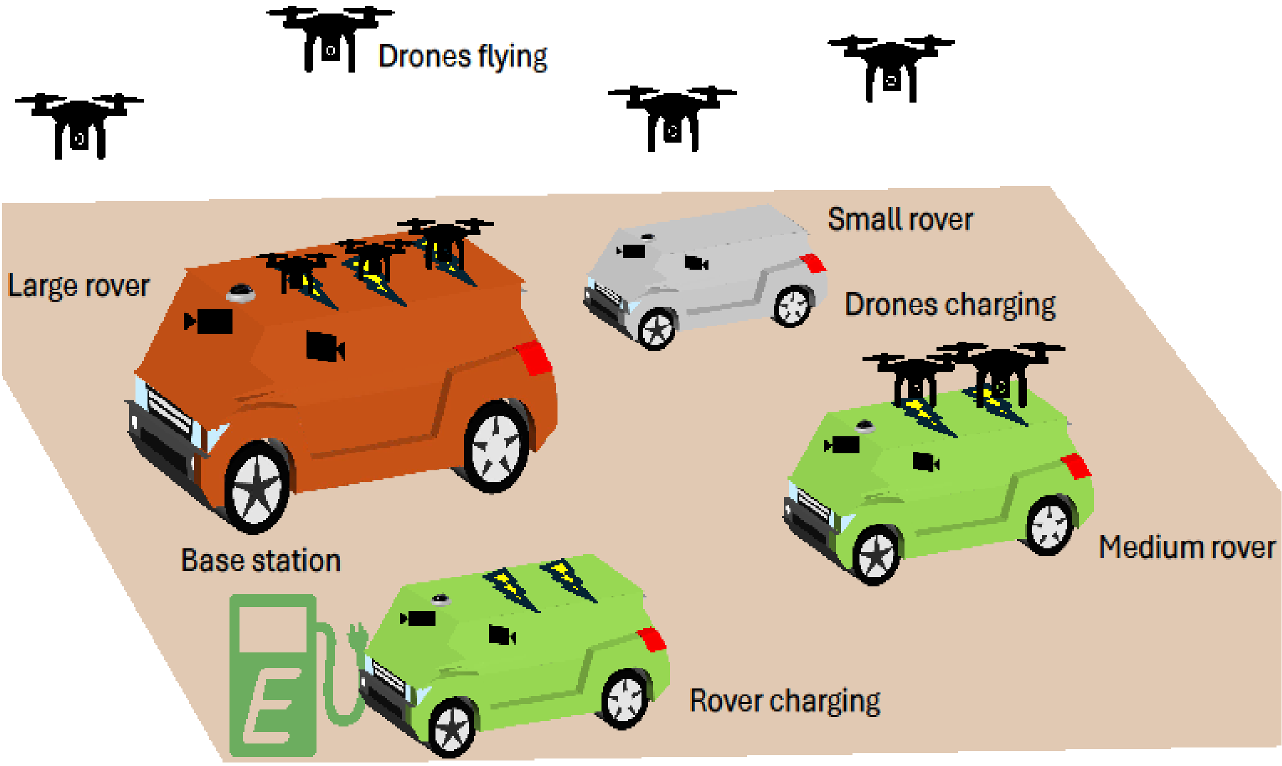
UAV: Unmanned Aerial Vehicle (Drone)

UGV: Unmanned Ground Vehicle (Rover)

- Large-scale response missions need fast coverage in unsafe or hard-to-access areas.
- UAV battery constraints limit mission duration and field coverage.
- Fixed charging infrastructure lacks flexibility in dynamic environments.
- Coordinated UAV-UGV planning can extend mission time and improve coverage.
- UAVs for aerial mobility & UGVs for ground support and mobile charging.

Research Problem

- Prior arts lack coordinated planning for UAV routing, UGV movement, & rendezvous-based charging.
- Energy-aware UAV-UGV mission plans with mobile charging support.
- Address limits of fixed charging infrastructure
- Reliable field coverage under battery and time constraints.



Challenges and Goals

Challenges

- Modeling coupled UAV routing, UGV movement, and mobile charging decisions.
- Limited UAV battery capacity for very large missions.
- UAVs and UGVs must coordinate at safe charging points for rendezvous-based charging.
- Limited domain awareness, due to a lack of mobile charging support.

Goals

- Build an energy-aware UAV-UGV planning framework.
- Coordinate UAV field visits with UGV mobile charging support.
- Maximize Field of Interest (FOI) coverage under battery constraints.
- Compare ILP reliability with RL adaptability.
- Validate routes through simulation.

Proposed Approach

Inputs

- BS, FOIs, SCPs coordinates
- Drone-only FOIs coordinates
- Number of Drones/ Rovers
- KAPPA, speed, battery
- Internal power, charging power
- Battery threshold and critical reserve

Planner

ILP (offline)

RL (online)

Outputs

ILP (offline) →
- ILP outputs
- Waypoints for ArduPilot
- Resulting routes

RL (online) →
- Trained model
- Resulting routes
- Waypoints for ArduPilot

Preprocessor → **Simulator/ Validator** → **Simulated Trajectories**

ILP-RL Planning Framework

Common Energy and Motion Model

- UAVs visit fields of interest, while UGVs support mobile charging at safe charging points.
- Distance between mission nodes is computed from GPS coordinates.

- $t_{ij}^{a} = \frac{\boldsymbol{d_{ij}^{a}}}{\boldsymbol{v_a}}$
- $E_{ij}^{d} = \kappa_d d_{ij}^{d} + \left(P_d + P_d^{\mathrm{hov}}\right) t_{ij}^{d}$
- $E_{ij}^{r} = \kappa_r d_{ij}^{r} + P_r t_{ij}^{r}$

- t_{ij}^{a}: Travel time
- $\boldsymbol{d_{ij}^{a}}$: distance from node $i$to node j
- $\boldsymbol{v_a}$: vehicle speed
- $a \in \{\text{drone}, \text{rover}\}$

- E_{ij}^{d}, E_{ij}^{r}: Energy consumed
- κ_d, κ_r: distance-based energy coefficients
- P_d, P_r: internal power consumption
- P_d^{hov}: Power for drone hovering.

ILP-RL Planning Framework

ILP Objectives

1. Maximize FOI coverage
2. Minimize mission makespan within the same coverage

- $\max\left(\mathcal{F}_{visit}\right)$
- $\mathrm{T_{ms}} = \min\left(\max_{\mathrm{d}\in\mathcal{D}} \mathrm{T_d}\,,\ \max_{\mathrm{r}\in\mathcal{R}} \mathrm{T_r}\right)$

- $\mathcal{F}_{visit}$: Number of FOIs visited
- $\mathrm{T_{ms}}$: Mission makespan
- $\mathrm{T_d}, \mathrm{T_r}$: Mission time of drone & rover

- Mission has 10 FOIs, 5 drones, and 2 rovers.
- Configuration A visits 10 FOIs with $\mathrm{T_{ms}} = 5.70h$.
- Configuration B visits 8 FOIs with $\mathrm{T_{ms}} = 2.98h$.
- Configuration C visits 10 FOIs with $\mathrm{T_{ms}} = 6.20h$.
- ILP selects **Configuration A**, because FOI coverage has a higher priority and shorter mission time.

ILP-RL Planning Framework

RL Formulation

- Models UAV-UGV coordination as a finite-horizon Markov decision process.
- Learns routing and charging decisions through environment interaction.
  - $\mathrm{obs}_{\mathrm{len}} = 3(\mathcal{D} + \mathcal{R}) + \mathcal{F} + 1$ (Step count)
- Each UAV and UGV selects its next destination from the shared node set.
  - $N = \mathrm{BS} \cup \mathcal{F} \cup \mathcal{S}$
  - $\mathcal{A} = \{0,1,\dots,(N-1)\}^{\mathcal{D}+\mathcal{R}}$

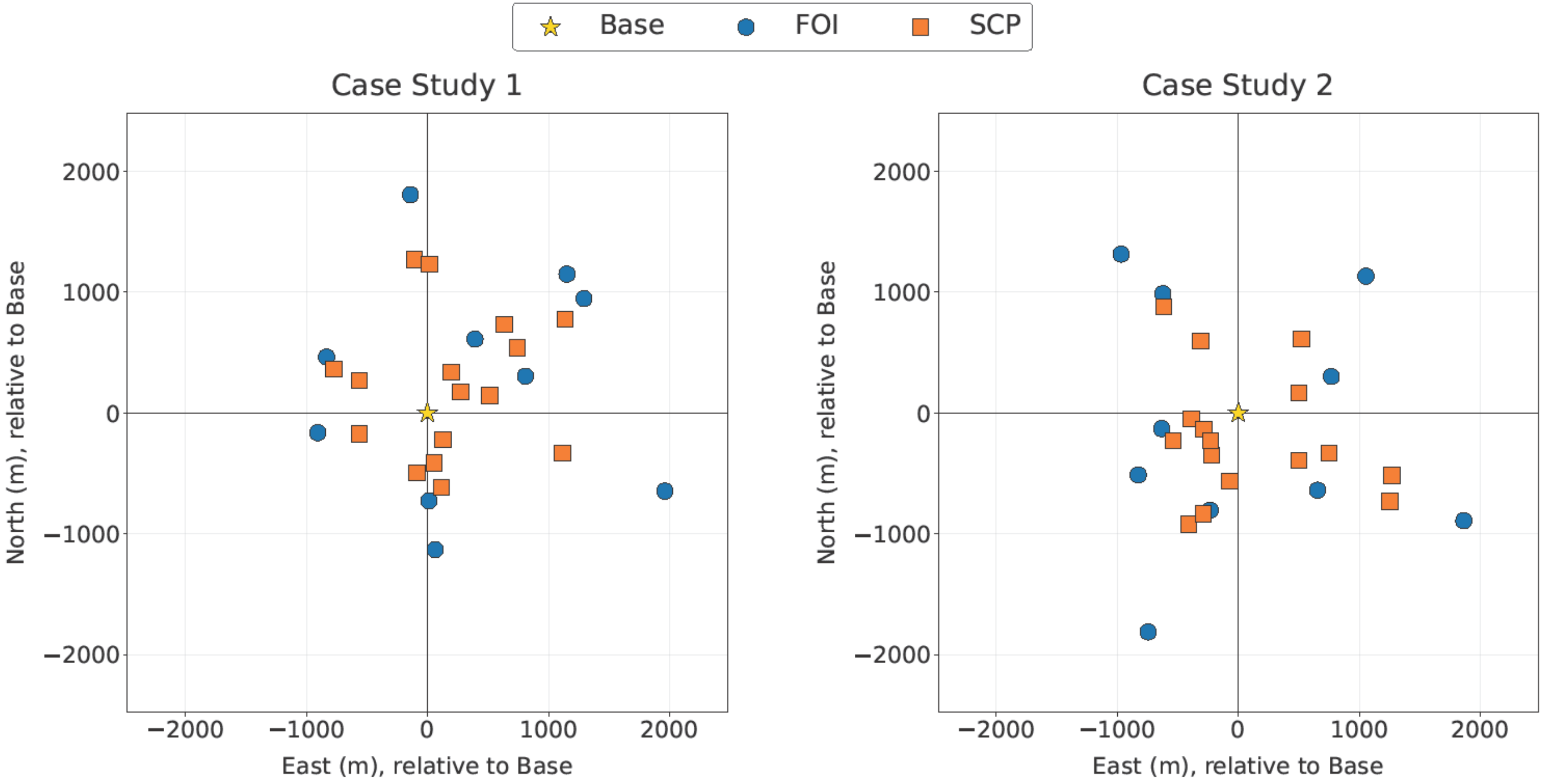
- $\mathcal{D}$: Number of UAVs
- $\mathcal{R}$: Number of UGVs
- $\mathcal{F}$: Number of FOIs
- BS: Base station
- $3(\mathcal{D} + \mathcal{R})$:Latitude, longitude, & battery level for each UAV & UGV

- $\mathcal{A}$: Joint action space for all UAVs and UGVs
- N: Shared node set containing BS, FOIs, & SCPs
- $\mathcal{S}$: Safe charging points

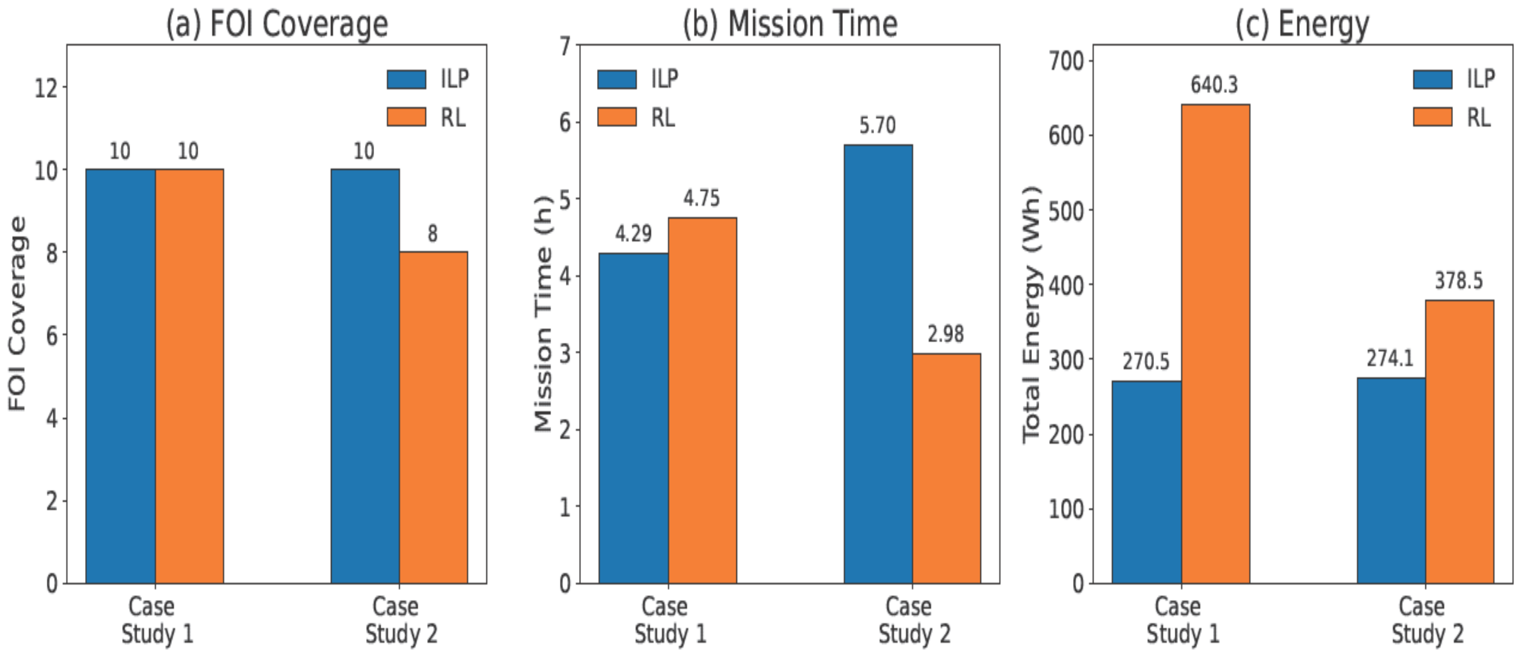
Evaluation

- Compare ILP-based offline planning and RL-based online planning using the same mission inputs.
- Study how different FOI and SCP layouts affect planner performance.
- Measure how each planner handles:
  - FOI coverage
  - Charging coordination
  - Mission completion time
  - Total energy consumption

- **Case Studies**
  - 1 base station.
  - 10 FOIs: 2 shared and 8 drone-only.
  - 16 safe charging points.
  - 5 UAVs and 2 UGVs.



Evaluation



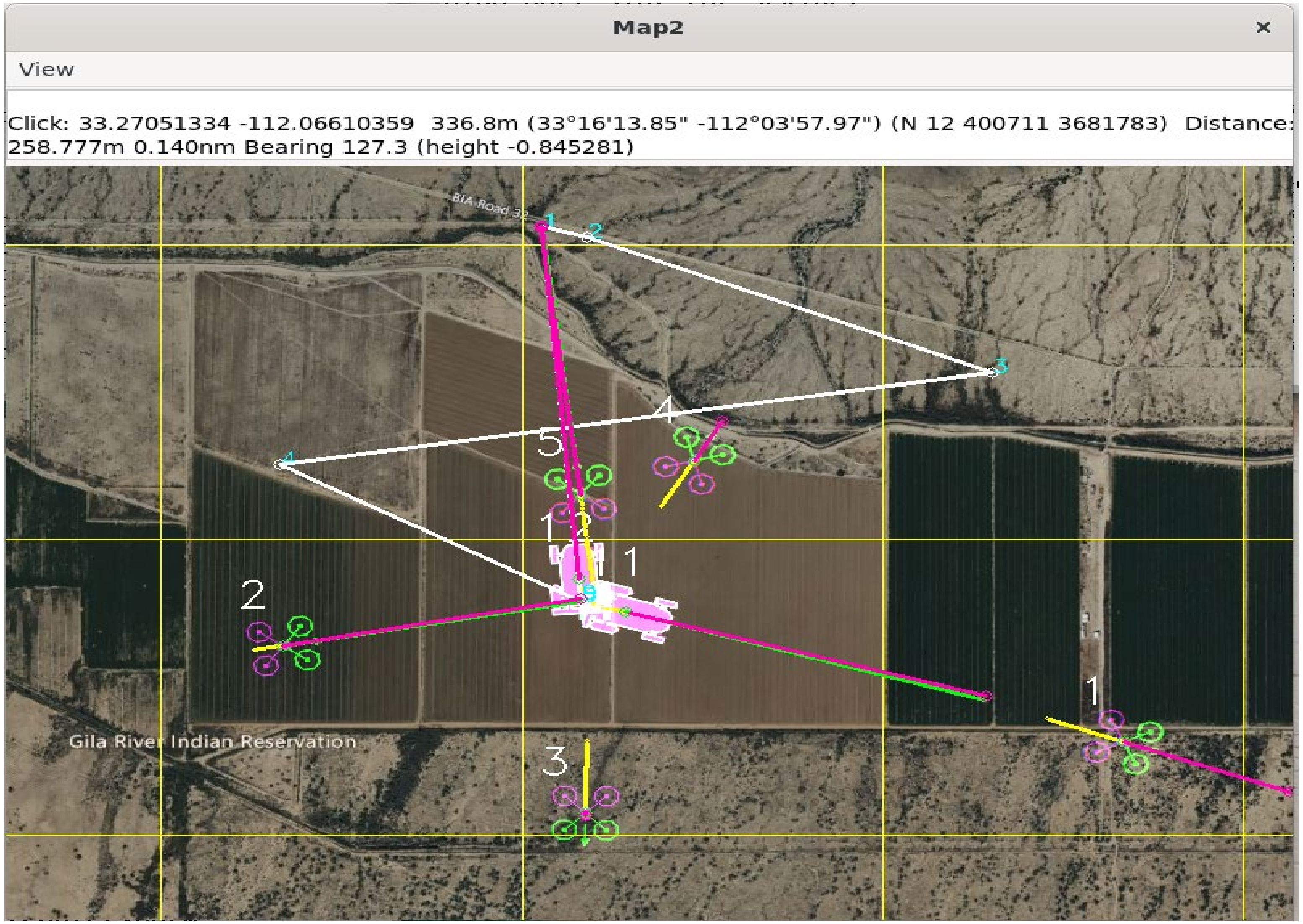
Case Study	Method	Planner Execution Time (s)	FOI Coverage
Case Study 1	ILP	23.9	10
Case Study 2	ILP	29.6	10
Case Study 1	RL	0.5	10
Case Study 2	RL	0.5	8

ILP vs. RL Performance Comparison

- ILP achieves complete FOI coverage in both case studies.
- RL completes Case Study 2 faster, but visits only 8 out of 10 FOIs.
- ILP uses less total energy through better route and charging coordination.

- RL runs much faster than ILP.
- ILP fits offline planning with known missions.
- RL is better suited for quick online adaptation, but may sacrifice coverage in harder layouts.

Simulation-Based Validation of Planner



- Convert planner routes into ArduPilot waypoint files.
- Validate UAV and UGV route feasibility in simulation.
- Pre-set drone battery using the total mission energy from ILP and RL, since ArduPilot does not model in-mission charging.
- Connect planning outputs to executable robotic missions.

Conclusion & Future work

- Proposed an energy-aware planning framework for collaborative UAV-UGV missions.
- ILP achieved more reliable FOI coverage and lower total energy consumption across both case studies.
- RL provided faster execution time, showing potential for online adaptation when mission conditions change.

- Extend the framework to larger mission areas with more UAVs, UGVs, FOIs, and SCPs.
- Explore hybrid planning that combines ILP reliability with RL adaptability.

ICCAD

Thank you for your attention !

www.linkedin.com/in/pawan-kumar-7ab62a16a

pkumar97@asu.edu

ASU KIM Lab Page: https://labs.engineering.asu.edu/kim/

More contact: https://hokeun.github.io/