Distributed multi-UAV Optimal Path Planning for Surveying Open Surface Minefields

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Introduction

- Real-time knowledge of the mining area is crucial for modern mining operations.
- Satellite images and aerial photographs provide a broad overview but lack detailed information on the damage caused by mining.
- Photogrammetry offers a solution for acquiring detailed information, but a closer look is needed. Unmanned Aerial Vehicles (UAVs), or drones, provide a feasible alternative to human teams for acquiring detailed information on the mining site.
- UAVs offer a cost-effective and efficient solution, reducing risks, costs, and time constraints associated with human deployments.
- However, UAVs have limited battery life and can cover only a limited area per flight.

- A high-end drone with battery capacity of 3500mAh can fly only for up to 34 minutes on a single charge.
- Flight time of an autonomous drone which uses sensors like LiDAR and RGB-D cameras for navigation and terrain following becomes shorter.

Fig : Drone model **Source:** Robotics & Control Lab @I ITR India

Research questions:

- Global planning: given a set of POIs extracted from a satellite image, how to cover maximum number of POIs by a set of UAVs with limited battery life.
- Local planning: given a set of assigned POIs to a UAV, how to design a robust terrain-following local path planning algorithm to visit these POIs.

Mathematical Modeling

- **Global planner**
  - POIs assignment problem is a coverage problem: we cast this problem as a submodular maximization subject to partition matroid:

    We show our coverage utility function is submodular:

$$R: 2^P \rightarrow \mathbb{R}_{>0}$$

Given a set of candidate points to deploy each UAV $i \in \{1, \cdots, N\}$, the optimal assignment maximizes the utility function defined over the joint ground set $P = \cup_{i=1}^{N} P^i$:

$$P^* = \operatorname{argmax} R(\bar{P}) \;\; s.t \quad \bar{P} \subset P \quad |\bar{P} \cap P^i| \leq 1, i \in \{1, \cdots, N\}$$

- Deployment points are points that a UAV starts its planner to visit its assigned POIs.
- The coverage area of each UAV is considered a function of its battery life span.
- The coverage-area model takes into account the distance between the deployment point and the point the UAV is launched from and will return to.

- **Local planner**
  - Dynamics:

$$F_i = k_f \omega_i^2$$
$$M_i = k_m \omega_i^2$$

where, F_i and M_i are thrust force and moment respectively, k_f and k_m are thrust and drag coefficient respectively, i denotes number of propeller.

$$m \begin{bmatrix} \ddot{X} \\ \ddot{Y} \\ \ddot{Z} \end{bmatrix} = [R] \begin{bmatrix} 0 \\ 0 \\ F_1 + F_2 + F_3 + F_4 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ -mg \end{bmatrix} \quad \text{Translational Motion}$$

$$\begin{bmatrix} I_x \ddot{\phi} \\ I_y \ddot{\theta} \\ I_z \ddot{\psi} \end{bmatrix} = \begin{bmatrix} T_x \\ T_y \\ T_z \end{bmatrix} - \begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} \times \begin{bmatrix} I_x \dot{\phi} \\ I_y \dot{\theta} \\ I_z \dot{\psi} \end{bmatrix} \quad \text{Rotational Motion}$$

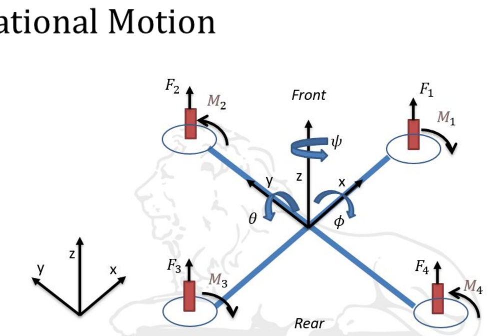

Fig: Schematic representation of Quadrotor

Methodology

- Satellite images are utilized to identify and extract POIs in the mining area.
- POIs are assigned to clusters using a k-means clustering approach to distribute inspection tasks among multiple UAVs.
- POIs are pruned using a deterministic sampling algorithm to generate potential deployment points.
- Terrain following and local path planning algorithms are developed to enable the UAVs to navigate and closely inspect the assigned POIs.
- A data-driven method is proposed, leveraging offline data from actual UAV maneuvers, to learn the UAV model and control policies for improved performance and efficiency.

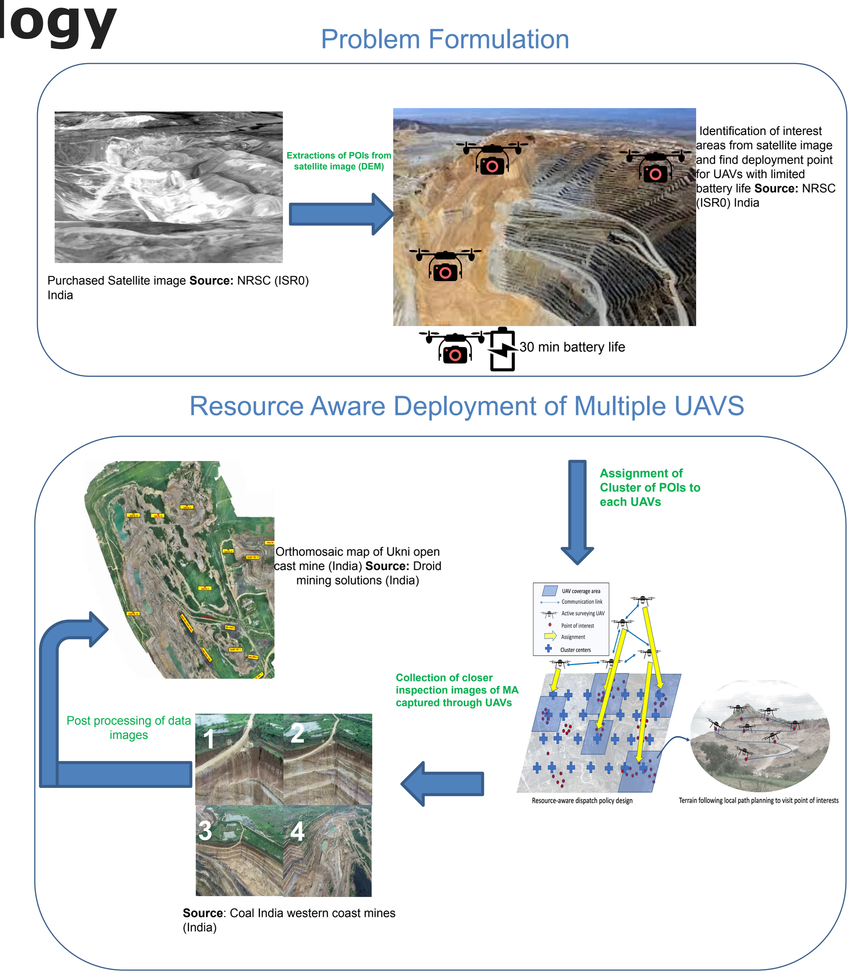

Fig : Workflow for mining area inspection using UAVs

Results

- Two-step deployment framework for deploying UAVs carried by possibly a set of trucks:
  - Given the set of POIs, global planner decides where the trucks should go so that the UAVs launched from them jointly cover the 'largest' possible subset of POIs considering the limited battery life of the UAVs

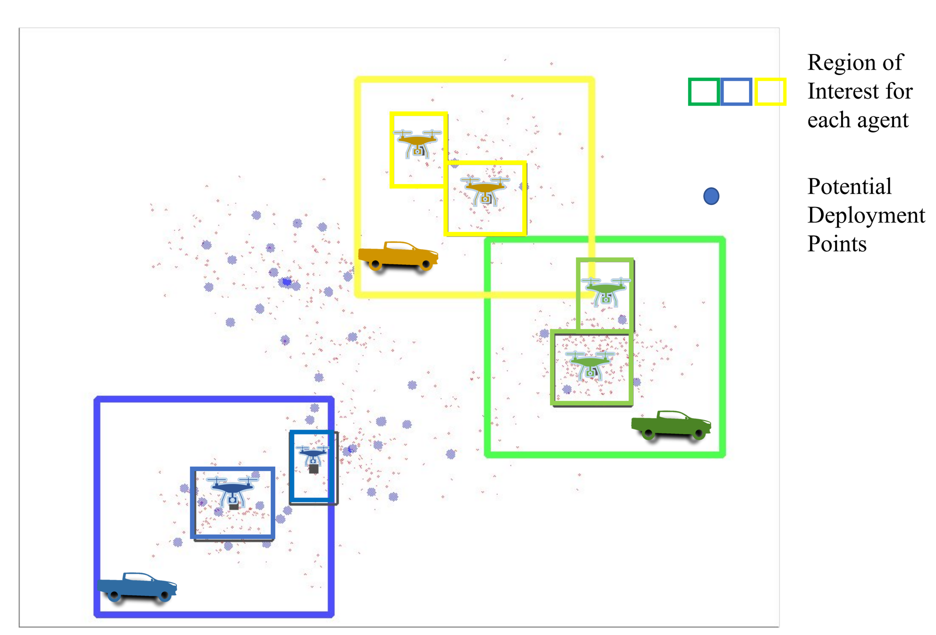

Fig : 2D Deployment Visualization ; Two step deployment ,where trucks carrying UAVs are deployed along an admissible path in the mining area and the UAVs are deployed afterwards

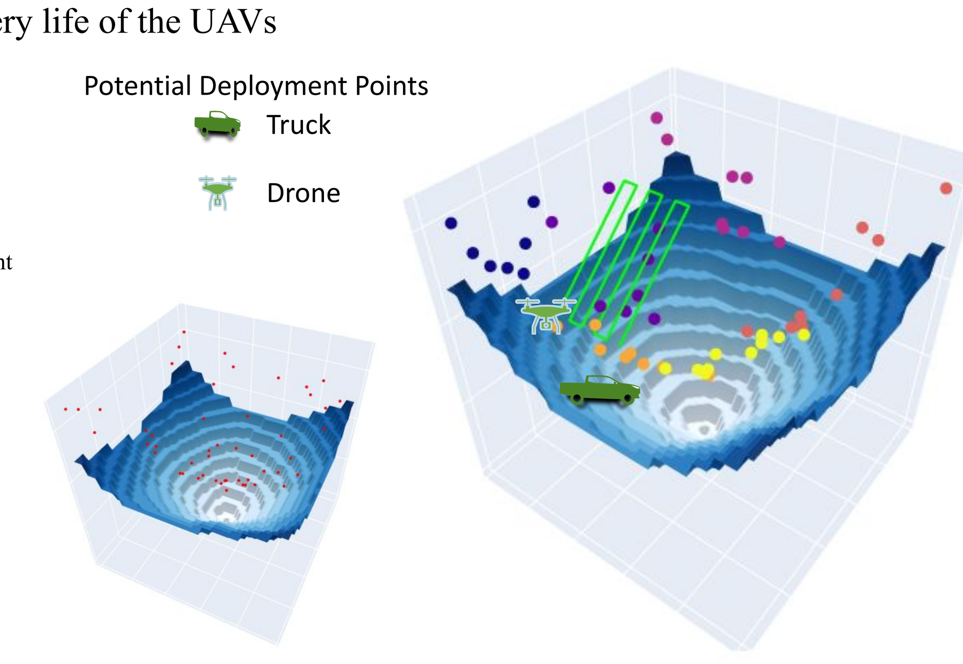

Fig : 3D Terrain Generation of mining pit along with POIs (left) , Clustering in the 3D world and proposing a planner for the UAV to follow to visit the POIs (right)

- Local planner executes local path following. Examples of local controller design
  - The path planning and trajectory following of drones for circular and Lissajous paths were simulated using Matlab and Simulink.
  - The PID controllers were used to optimize the controllers.
  - The simulation for swarm formation in Matlab was conducted using the concept of master-follower drones.

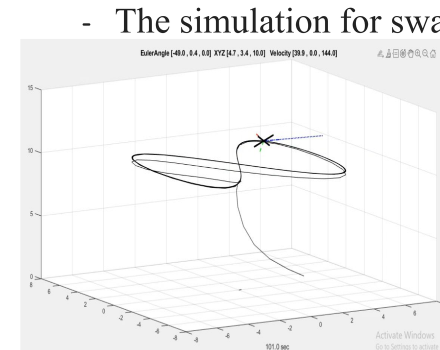

Fig : Circular path obtained through data driven method

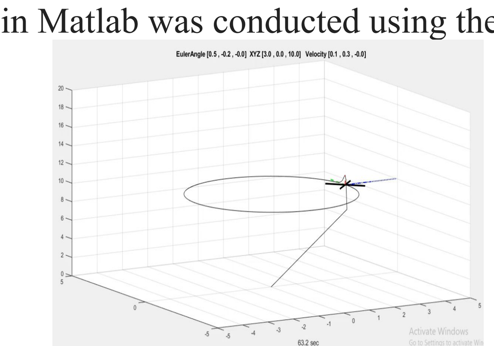

Fig : Lissajous path obtained through data driven method

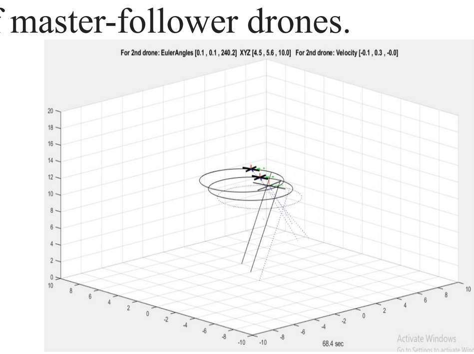

Fig : Swarm UAV path planning

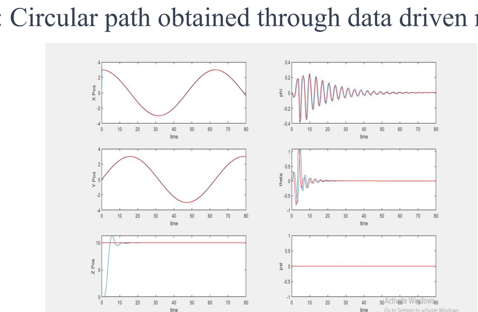

Fig : Actual vs desired path of Swarm UAVs

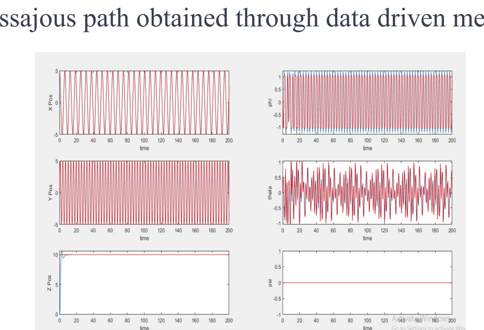

Fig : Actual vs desired path of Lissajous trajectory

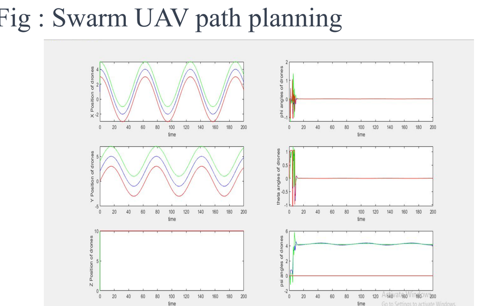

Fig : Actual vs desired path of Swarm UAVs

Key takeaways

- Real-time knowledge through photogrammetry for mining operations.
- Importance of monitoring surrounding rocks for safety and economic viability.
- Terrain following and local path planning for efficient monitoring.
- Simulation environment for realistic scenario evaluation.
- Research on data-driven UAV modeling and control using Contraction Theory.

Broader impact

- Improved safety for miners and surrounding communities.
- Environmental protection through early detection of hazards.
- Optimal resource management and reduced waste.
- Increased productivity and efficiency in mining operations.
- Cost savings compared to traditional methods.
- Promotes sustainable mining practices.

Conclusion

- UAVs enhance mining operations with real-time knowledge, safety, and productivity.
- UAV integration enables closer examination and informed decision-making.
- Monitoring via UAVs is a cost-effective alternative, reducing risks, costs, and time.
- We offered a resource-aware deployment strategy to deploy UAVs for maximum inspection utility given their limited battery life span. An effective data-driven local controller enabled visiting POIs in a terrain-following fashion.
- Our solution is a systematic deployment strategy that orchestrate deployment of a set of UAVs over a large open field based on the feedback from the current state of the area extracted from the top-down satellite/aerial imagery.

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