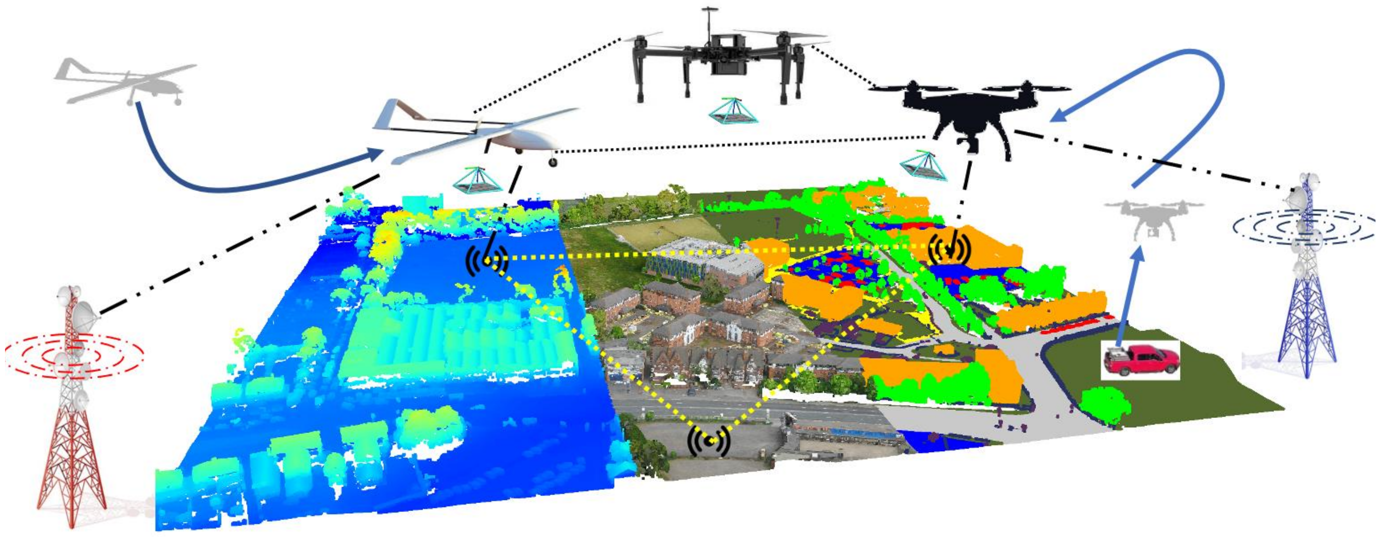
NRI: FND: COLLAB: Distributed Bayesian Learning and Safe Control for Autonomous Wildfire Detection

Nikolay Atanasov[1] Sicun Gao[2] Tajana Rosing[2] Baris Aksanli[3] [1]ECE, [2]CSE, UCSD [3]ECE, SDSU

Challenge

- Real-time environmental monitoring using an unmanned aerial vehicle (UAV) team



Technical Approach

- **Task A**: Online multi-modal terrain mapping
- **Task B**: Communication- and uncertainty-aware UAV trajectory planning
- **Task C**: Robot control with safety and stability guarantees

Scientific and Education Impacts

- Develop fundamental robot autonomy capabilities to support environmental monitoring
- UCSD-SDSU collaboration to increase undergraduate participation in robotics research

Broader Impacts

- Situational awareness for first responders
- Data collection for pre and post fire monitoring and fire spread simulation

Award ID#: 1830399
Award Date: October 2018

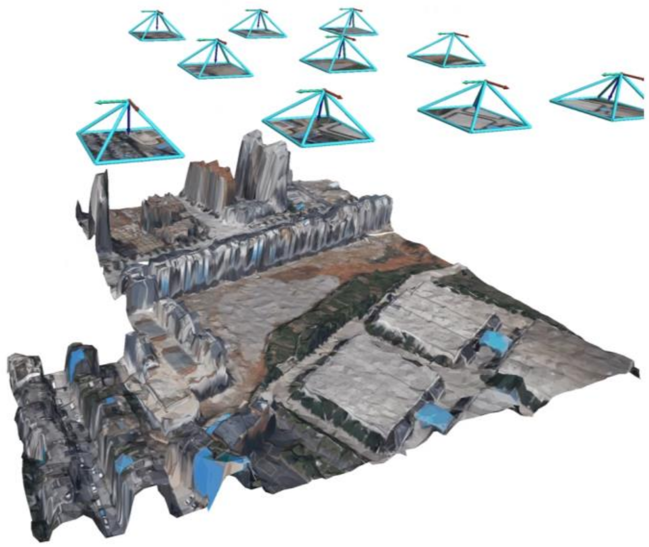
Motivation

North California Wildfires

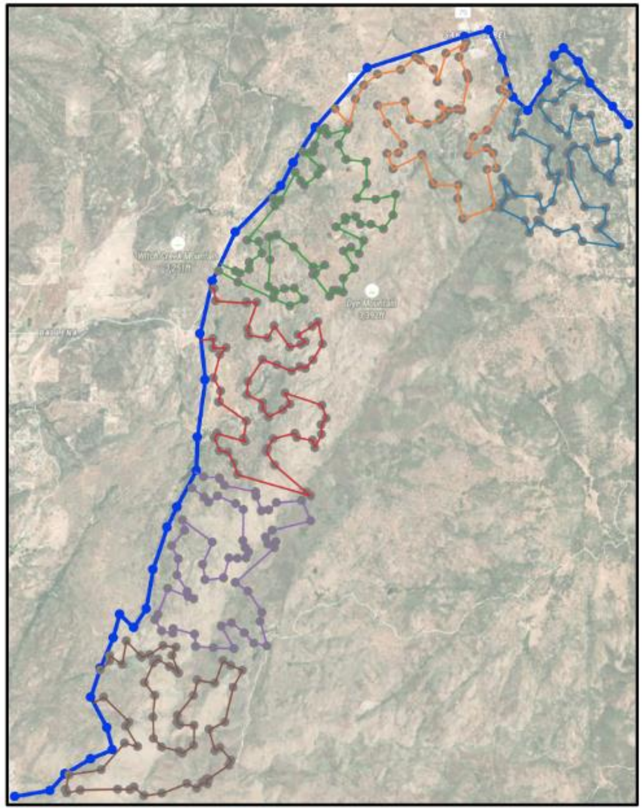
Smog over Los Angeles

- **Environmental monitoring** and **disaster response** are problems of growing importance that require persistent sensing and data collection
- **Persistent monitoring and early detection** are critical factors in mitigating damages to ecological systems and human infrastructure

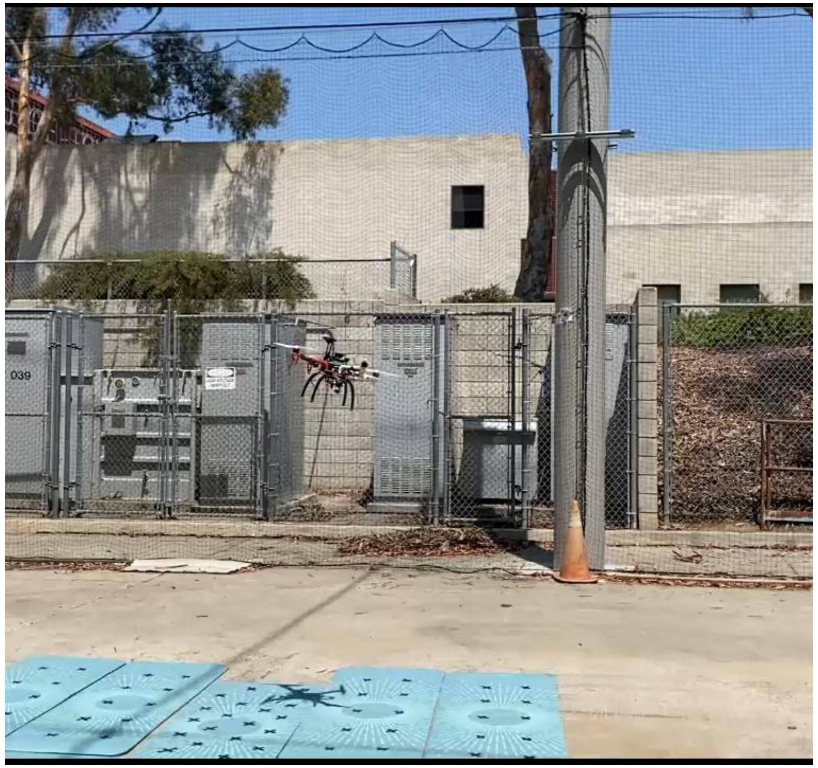
Project Overview



Task A: Online multi-modal terrain mapping



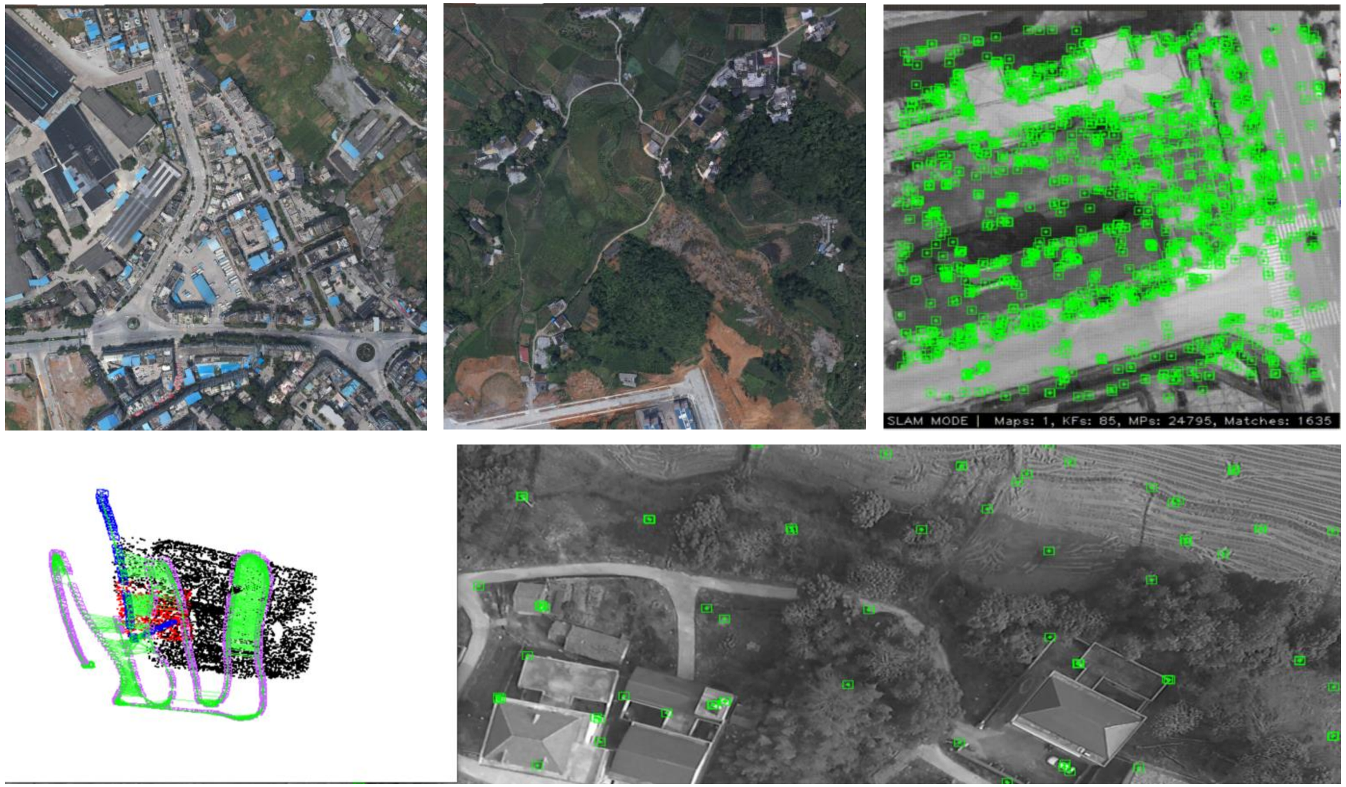
Task B: Comms-, uncertainty-aware trajectory planning



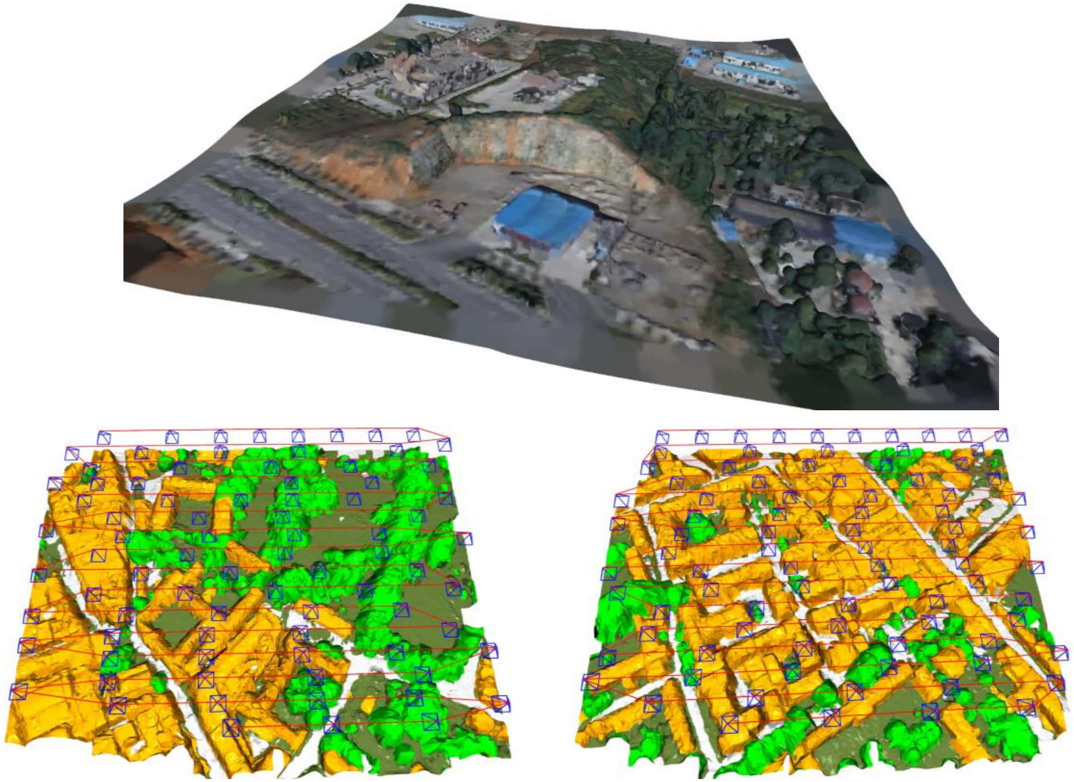
Task C: Robot control with safety and stability guarantees

Task A: Online Multi-modal Terrain Mapping

Input: streaming aerial RGB images and sparse depth of tracked features

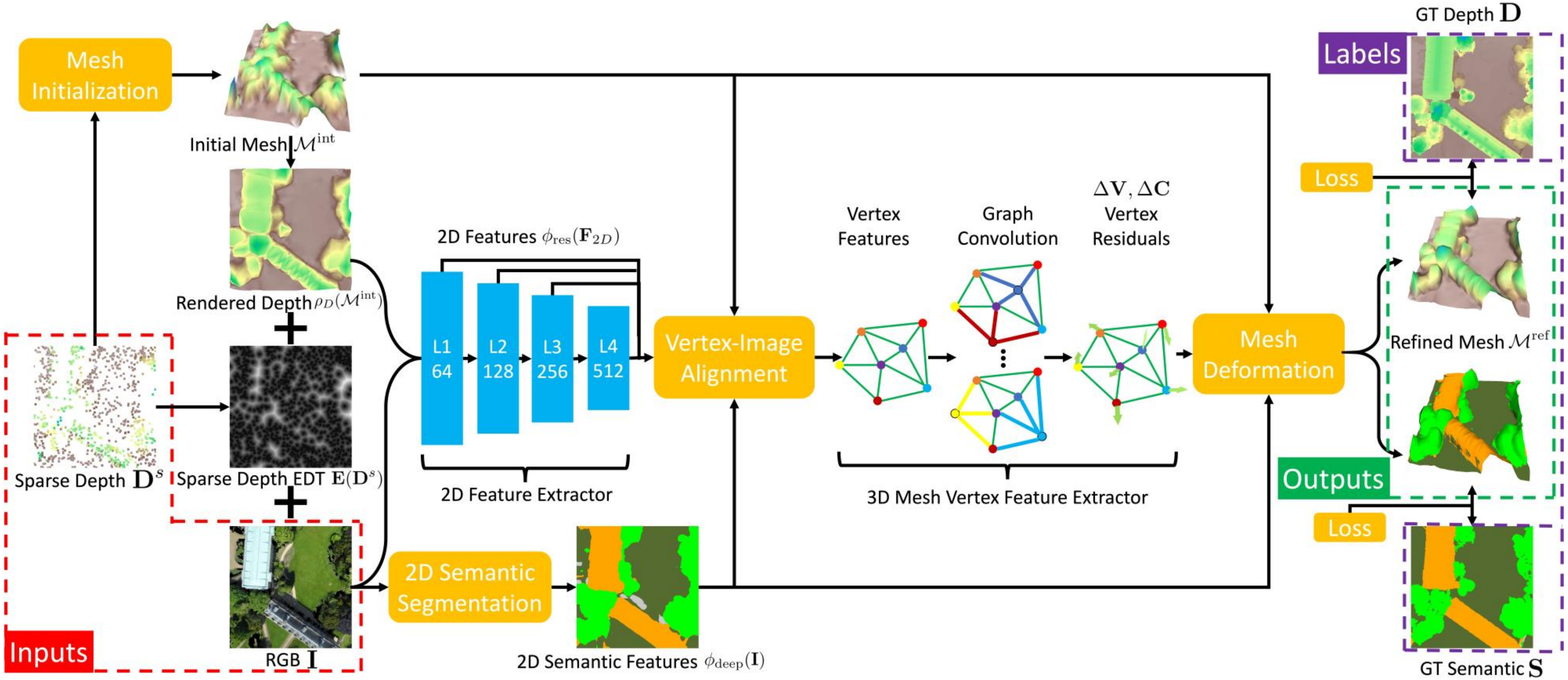


Output: semantically annotated mesh model of the environment



Task A: Online Multi-modal Terrain Mapping

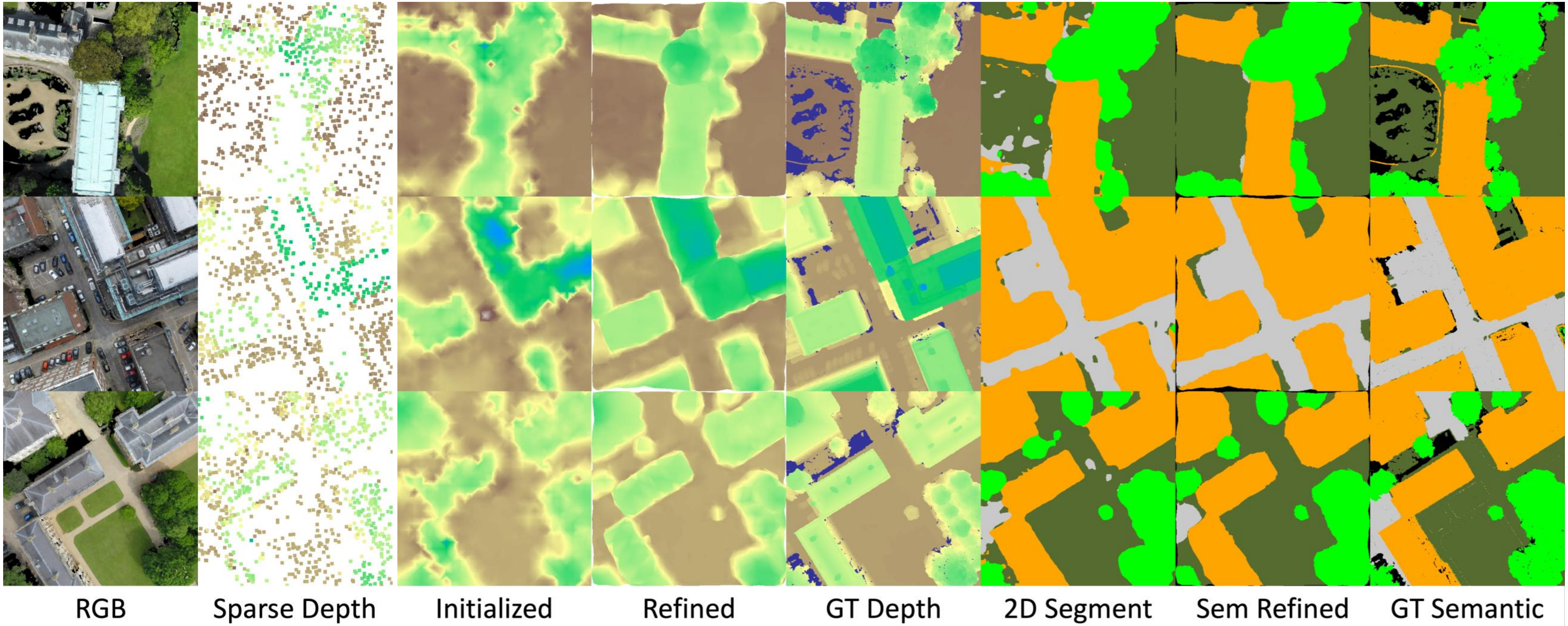
Major Contribution: Graph convolution neural network model to mesh vertex prediction, minimizing 3-D mesh and 2-D depth errors



Q. Feng, N. Atanasov, **"Mesh Reconstruction from Aerial Images for Outdoor Terrain Mapping Using Joint 2D-3D Learning,"** IEEE International Conference on Robotics and Automation (ICRA), 2021

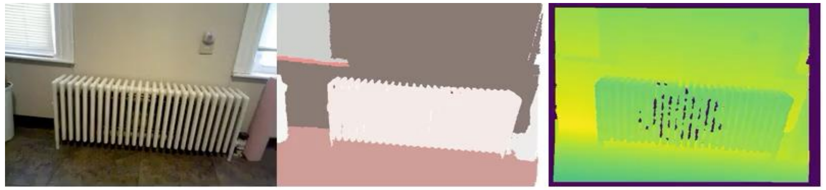
Q. Feng, N. Atanasov, **"TerrainMesh: Metric-Semantic Terrain Reconstruction from Aerial Images Using Joint 2D-3D Learning,"** submitted to IEEE Transactions on Robotics (T-RO)

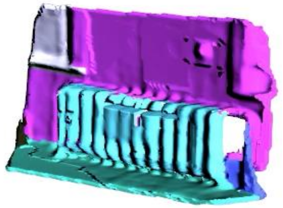
Task A: Online Multi-modal Terrain Mapping



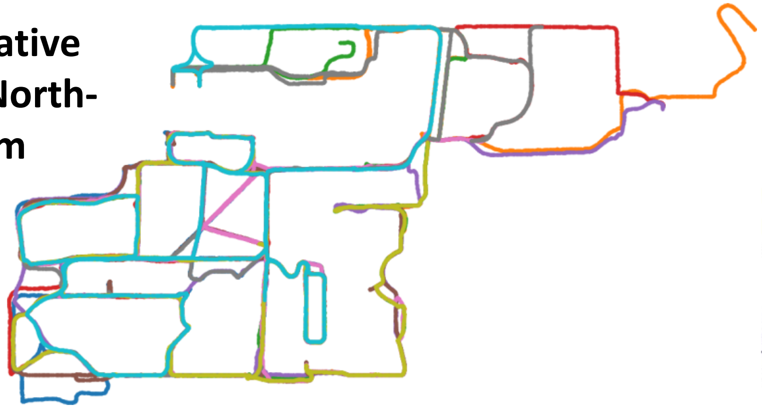
Task A: Other Achievements

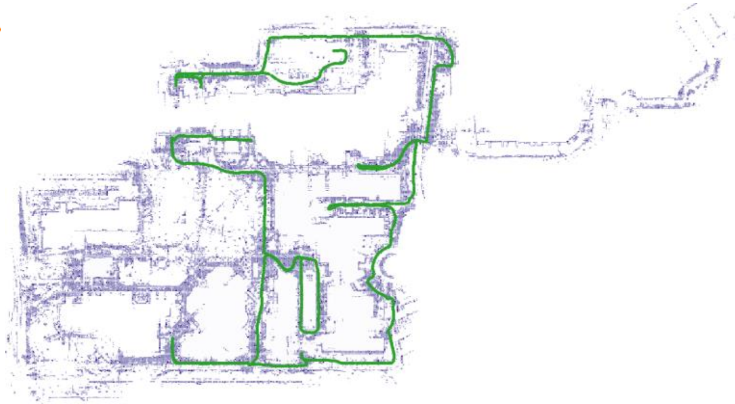
- Information filter occupancy mapping using decomposable radial kernels (**IROS 2019**)
- Dense incremental metric-semantic mapping via sparse Gaussian Process regression (**IROS, 2020**)
- Distributed Gaussian Process mapping for robot teams with time-varying communication (**ACC, 2022**)
- Dense incremental metric-semantic mapping for multi-agent systems via sparse Gaussian process regression (**submitted to TRO**)





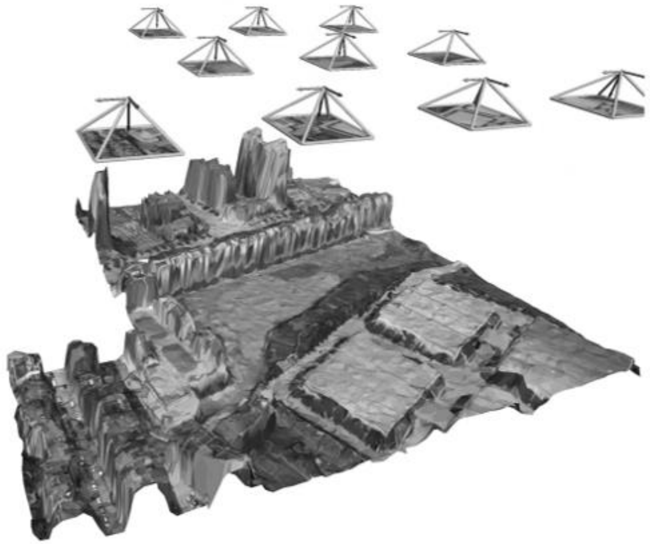
10 robot collaborative mapping UMich North-Campus Long-Term dataset



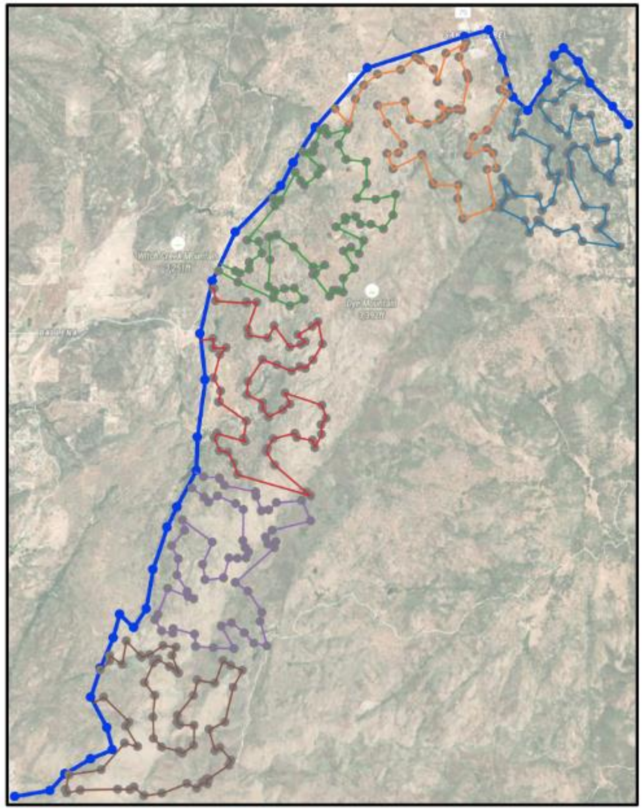


Indoor metric-semantic signed distance function reconstruction from streaming RGBD images, SceneNN dataset

Project Overview



Task A: Online multi-modal terrain mapping

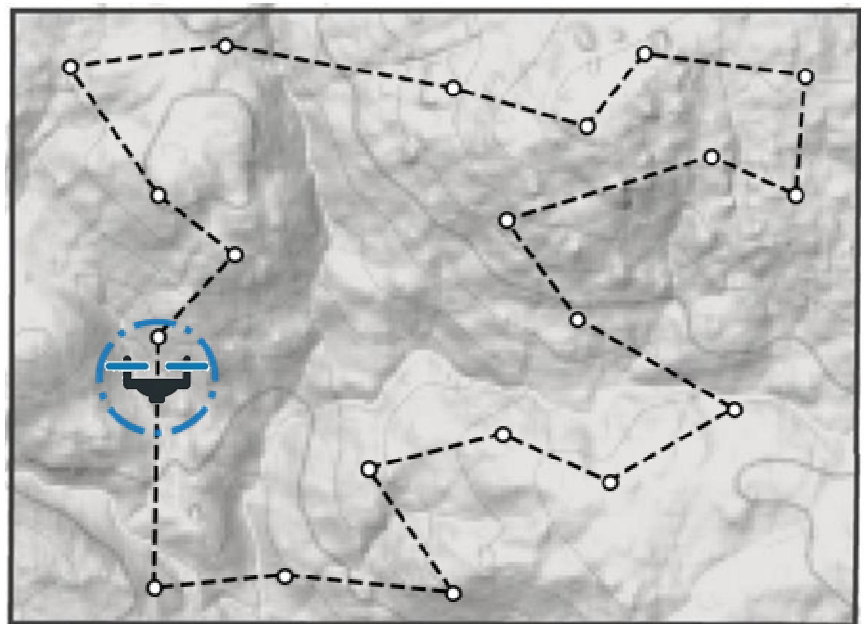


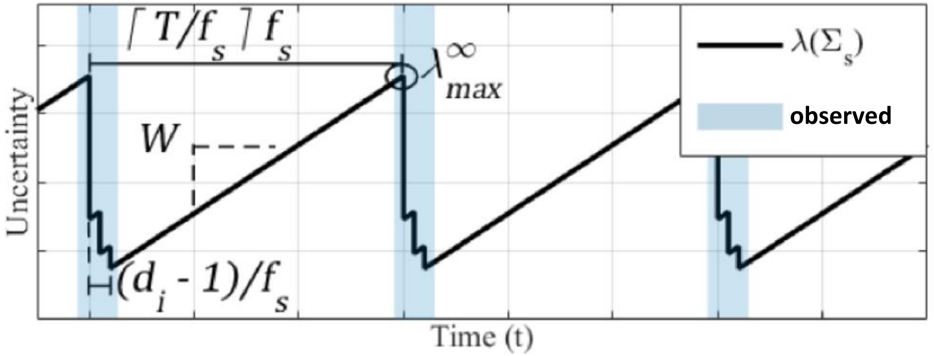
Task B: Comms-, uncertainty-aware trajectory planning

Task C: Robot control with safety and stability guarantees

Task B: Uncertainty-aware UAV trajectory optimization

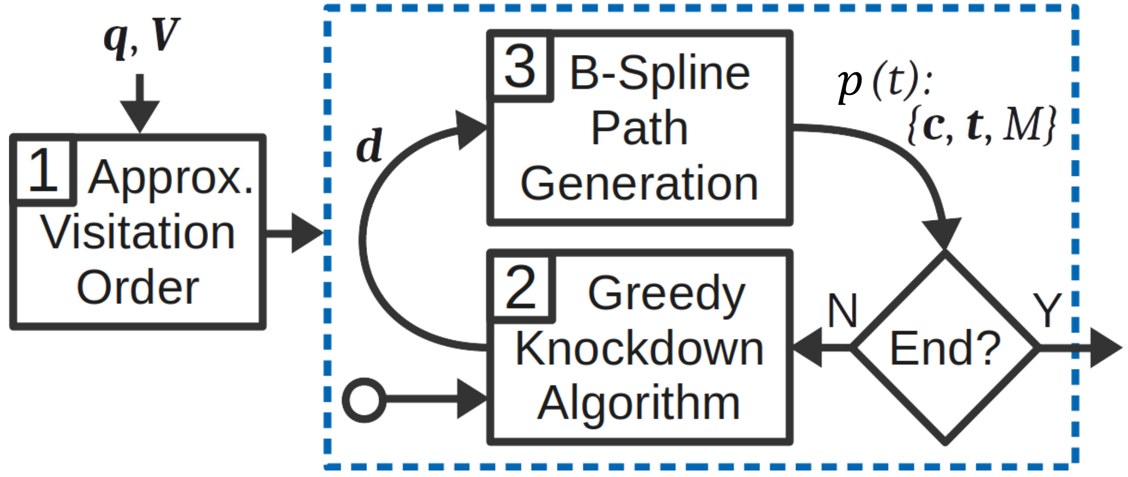
- **Input**: set of interest points to be observed
- **Output**: dynamically feasible UAV trajectory that observes the interest points
- How much time should be spent at each point?
  - Increased observation at one point decreases uncertainty at this point but the uncertainty at other points increases
  - Lower loop time → less uncertainty gain for all points
- **Objective:** Minimize max uncertainty at any point





Task B: Uncertainty-aware UAV Trajectory Optimization

- Calculate initial point order using a TSP solver
- Two-level optimization:
  - **Primary**: minimize time to observe each point plus loop travel time
  - **Secondary**: minimize B-spline jerk subject to velocity, acceleration, and minimum observation time constraints



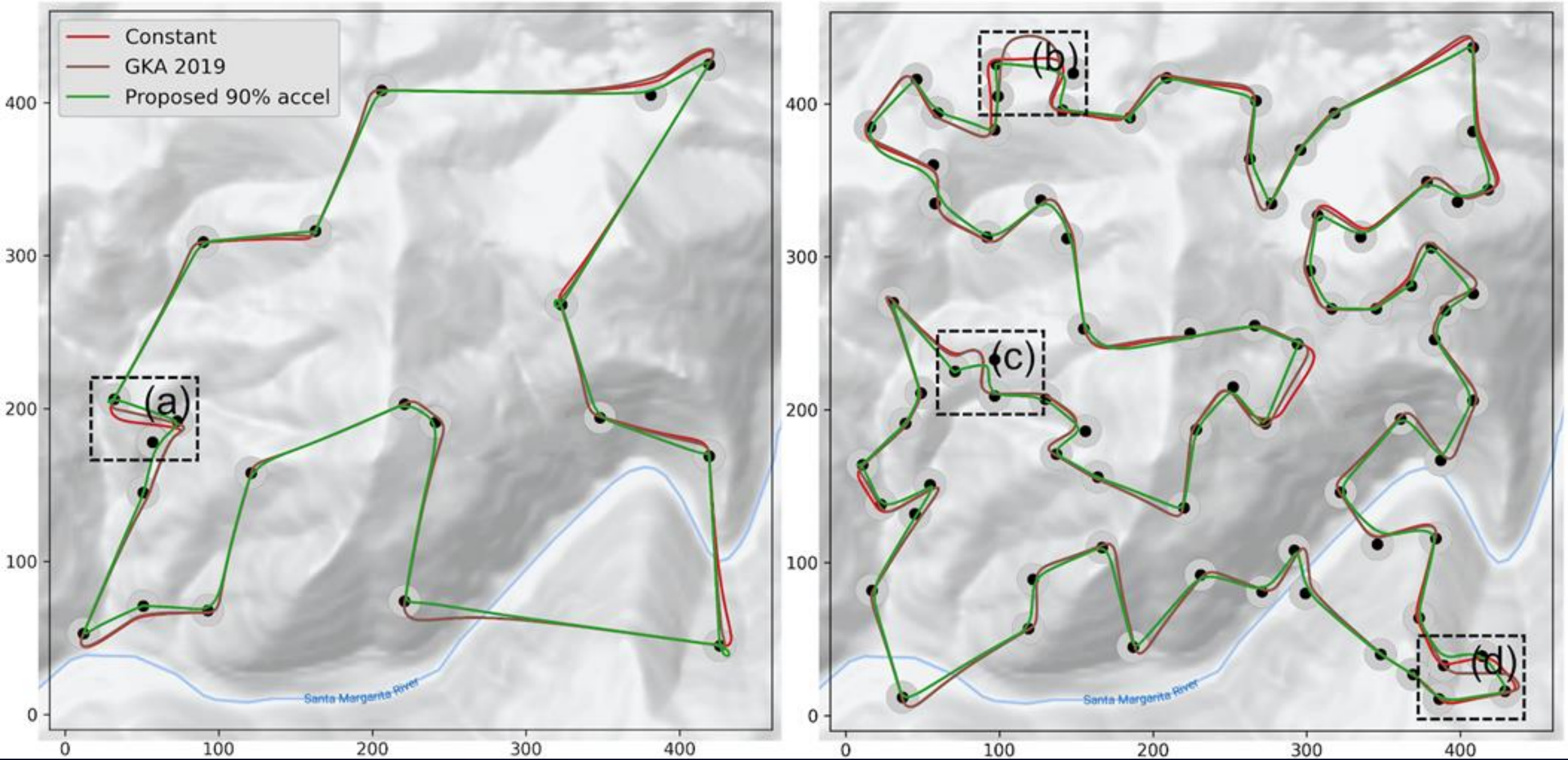
- **Greedy Knockdown algorithm** determines loop time and number of measurements per point to minimize maximum Kalman Filter uncertainty
- B-spline trajectory generation for each independent sensing region becomes a **Second Order Cone Program**

M. Ostertag, N. Atanasov, T. Rosing, "**Robust Velocity Control for Minimum Steady State Uncertainty in Persistent Monitoring Applications**," American Control Conference (ACC), 2019

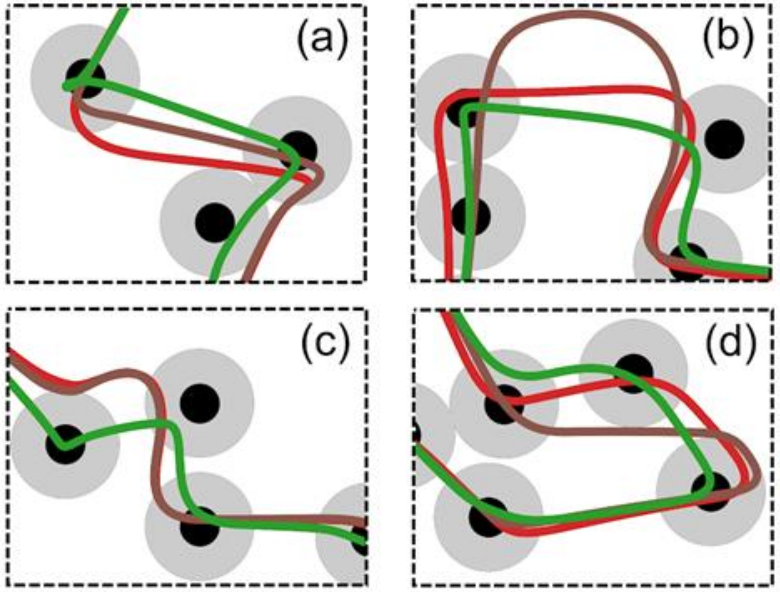
M. Ostertag, N. Atanasov, T. Rosing, ”**Trajectory Planning and Optimization for Minimizing Uncertainty in Persistent Monitoring Applications,**” submitted to the Journal of Intelligent and Robotic Systems, 2022

Task B: Uncertainty-aware UAV Trajectory Optimization

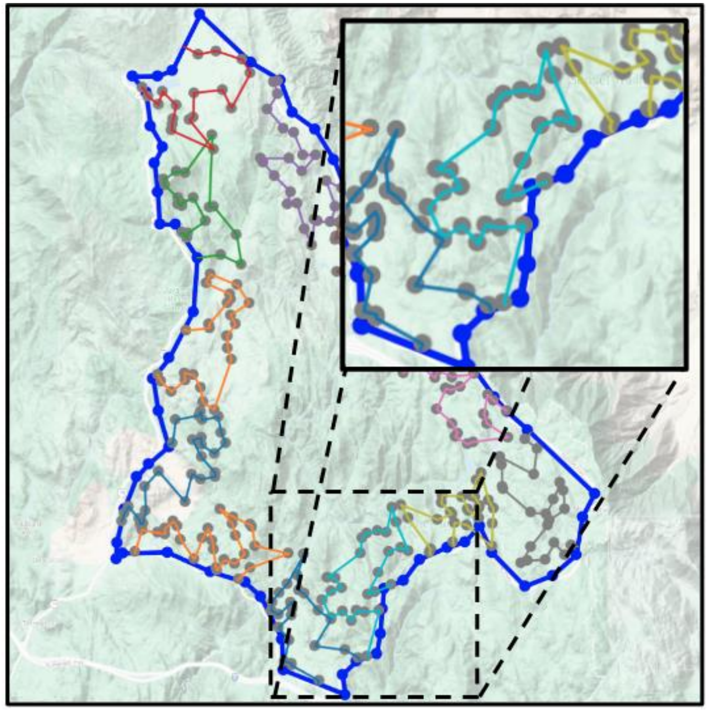
- **Example:** 20 (left) and 80 (right) points of interest spread across 50 acres around Santa Margarita River, CA (scalable to more points and area, depending on application)



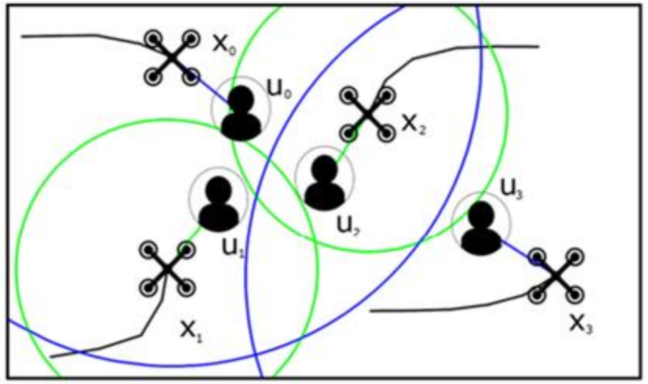
Focus on missed observations due to **constant velocity** and **GKA 2019** planners not considering dynamic constraints.



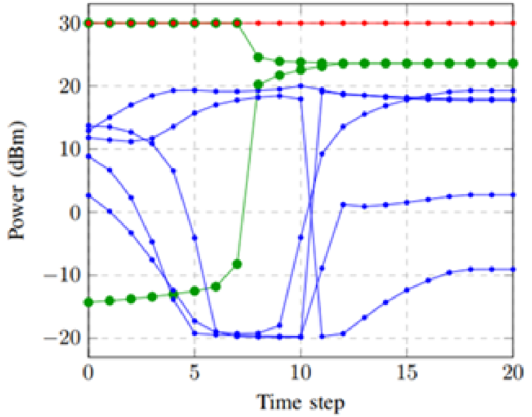
Task B: Other Achievements



Remote sensing with UAV and mobile recharging vehicle rendezvous (**DATE, 2022**)



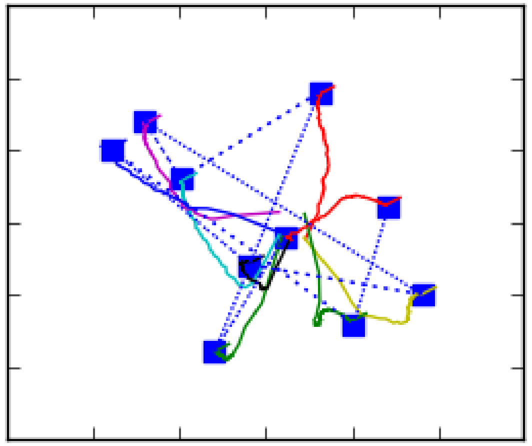
multiple channel, varied power



transmit power optimization

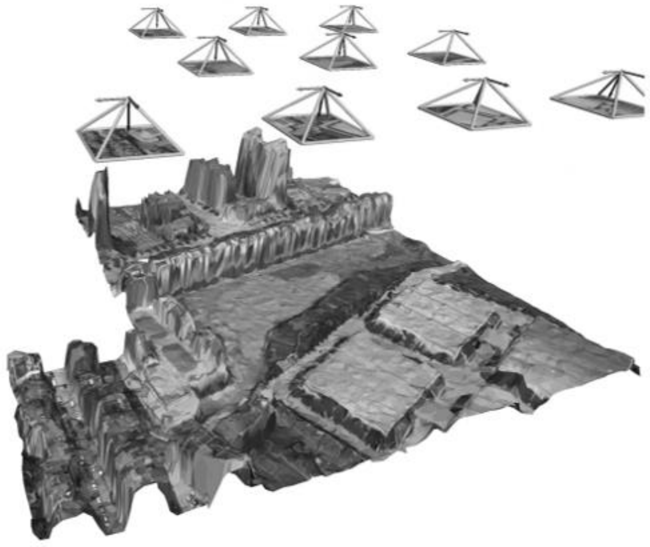
Frequency-aware trajectory and power control for multi-UAV systems **(DroneCom Workshop, 2021)**

- Maximize network capacity for UAVs assigned to human users
- Alternating optimization of UAV trajectories, RF channel, RF power

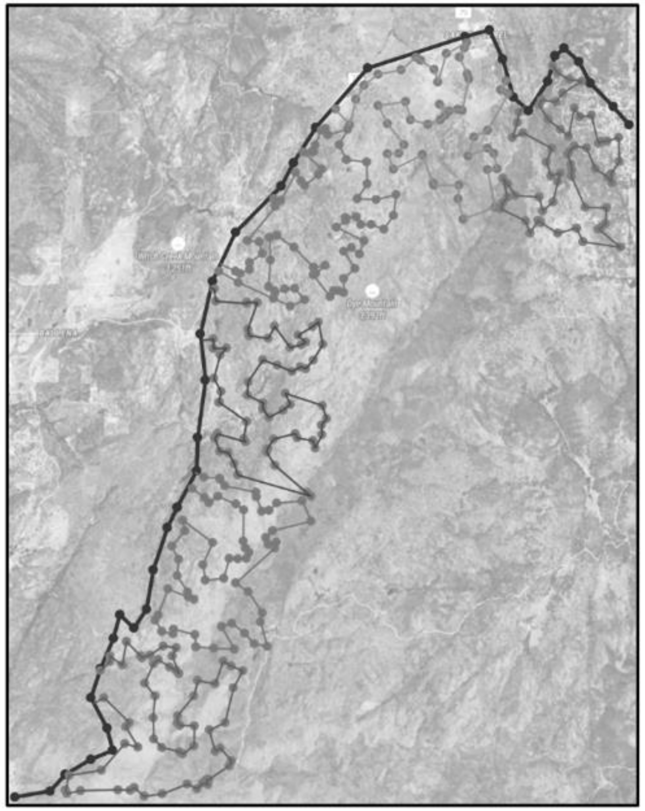


- Distributed node localization and cooperative estimation (**CDC, 2019, 2020**)
- Efficient training on edge devices using online quantization (**DATE, 2020**)

Project Overview



Task A: Online multi-modal terrain mapping

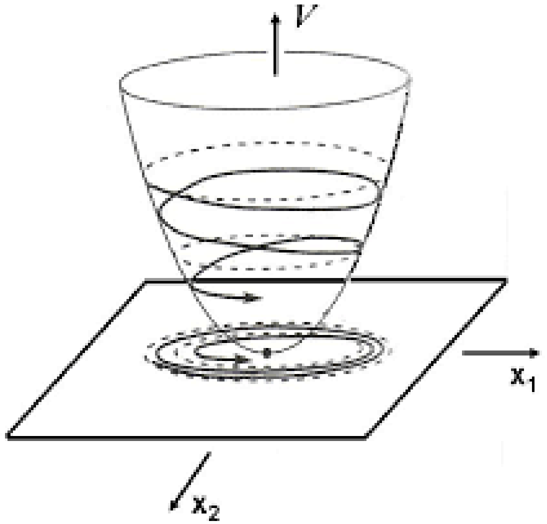


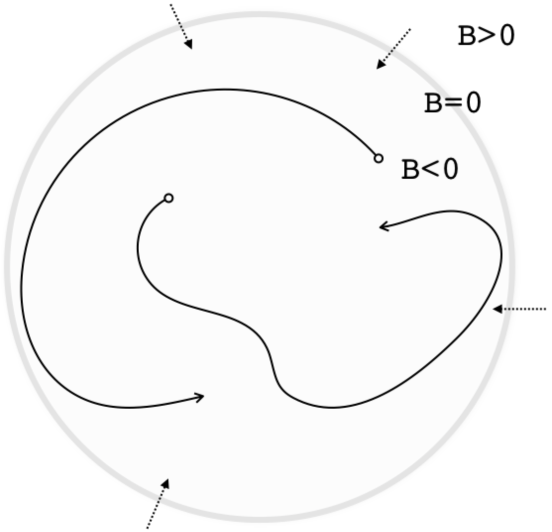
Task B: Comms-, uncertainty-aware trajectory planning

Task C: Robot control with safety and stability guarantees

Task C: Robot Control with Safety and Stability Guarantees

Major Contribution: learning methods for stability and safety certification of control policies





- A system is **stable** if we can construct a Lyapunov function to show that the system trajectories converge to an equilibrium point
- The goal is to find the right shape of **Lyapunov function** and certify a **Lie derivative conditions**

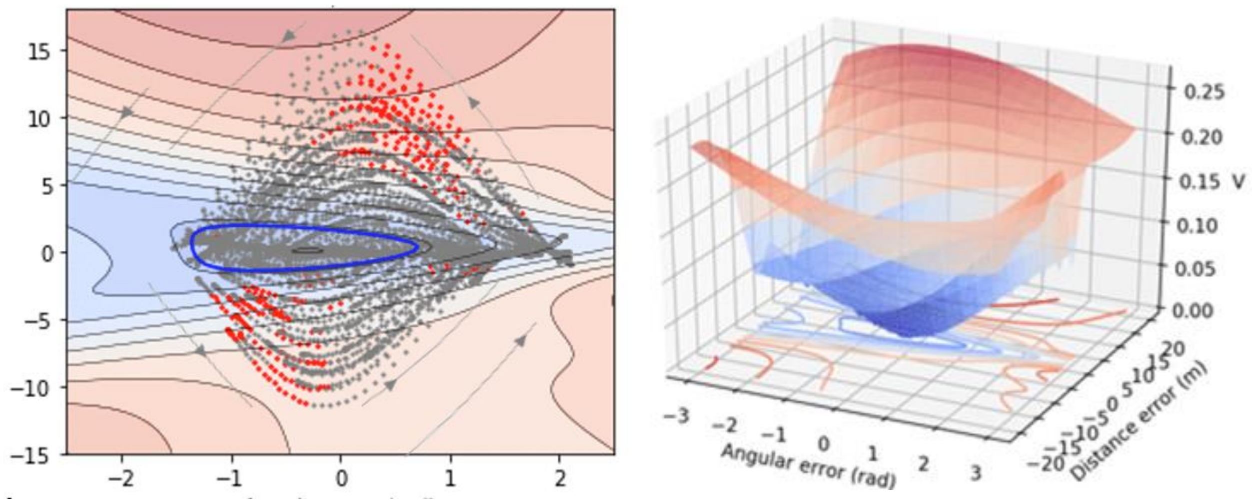
- A system is **safe** if we can construct a forward invariant set to show that the system trajectories never escape its boundary
- The goal is to find the right shape **barrier function** and certify a **Lie derivative condition**

Task C: Robot Control with Safety and Stability Guarantees

- The key to ensuring safety and stability is to find a certificate $V(x)$ and control policy $\pi(x)$ to produce inductive proofs:

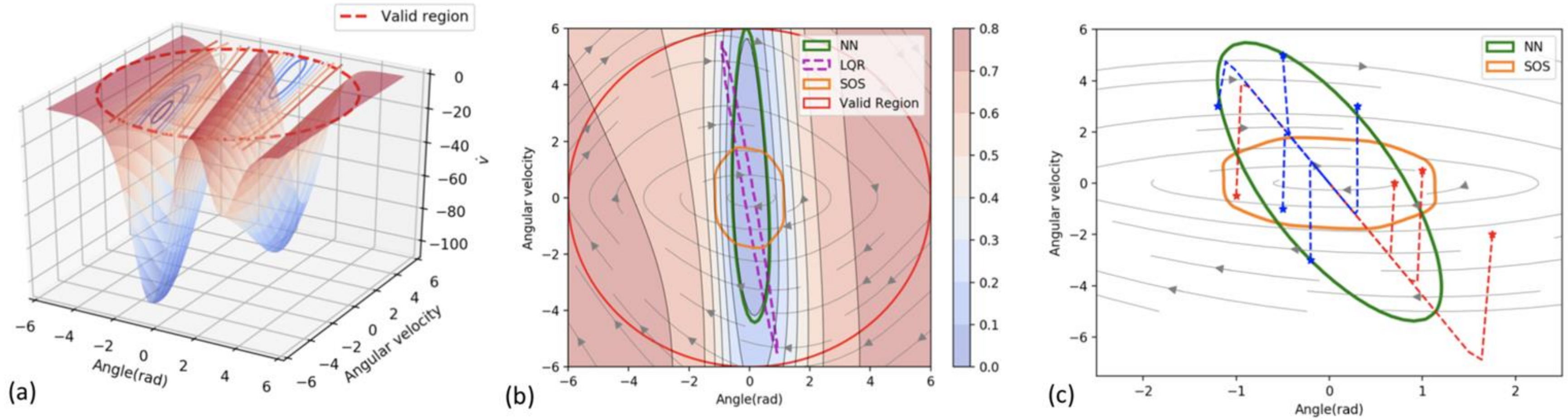
$$\exists V\ \exists \pi\ \forall x\ \Phi_f(V, \pi, x)$$

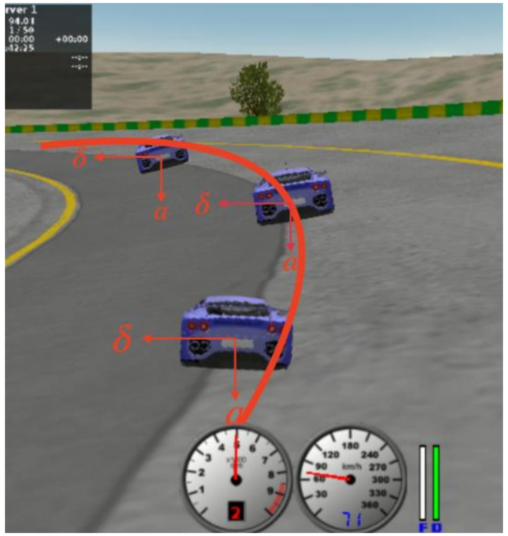
- Success of neural certificates:
  - Expressive function approximators for V and π
  - Scalable optimization for existential quantifiers
  - Scalable certification for universal quantifiers
- Much larger regions of attraction compared to existing methods: LQR, SOS, SDP

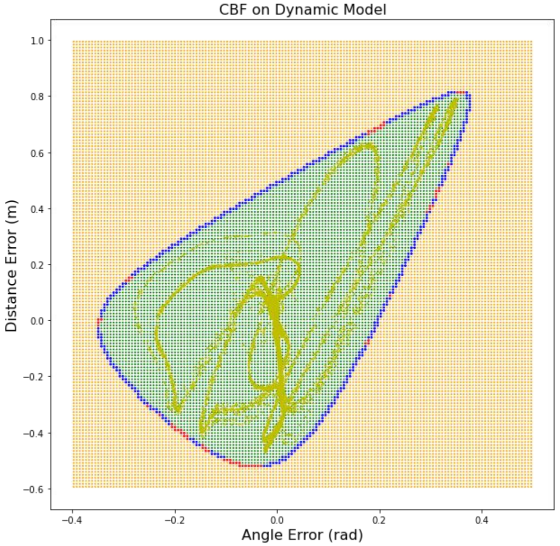


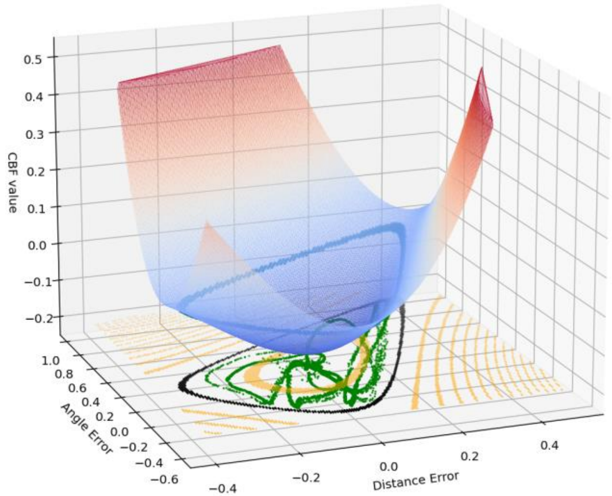
- **Since our initial work (NeurIPS 2019), this became a quickly growing area of significant interest**
- **Recently submitted survey paper:** C. Dawson, S. Gao, C. Fan, "**Safe Control with Learned Certificates: A Survey of Neural Lyapunov, Barrier, and Contraction methods**," arXiv 2202.11762

Task C: Robot Control with Safety and Stability Guarantees





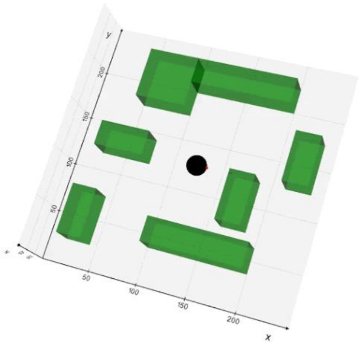


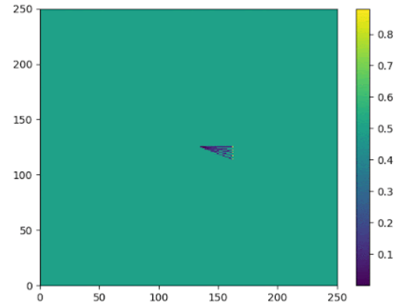


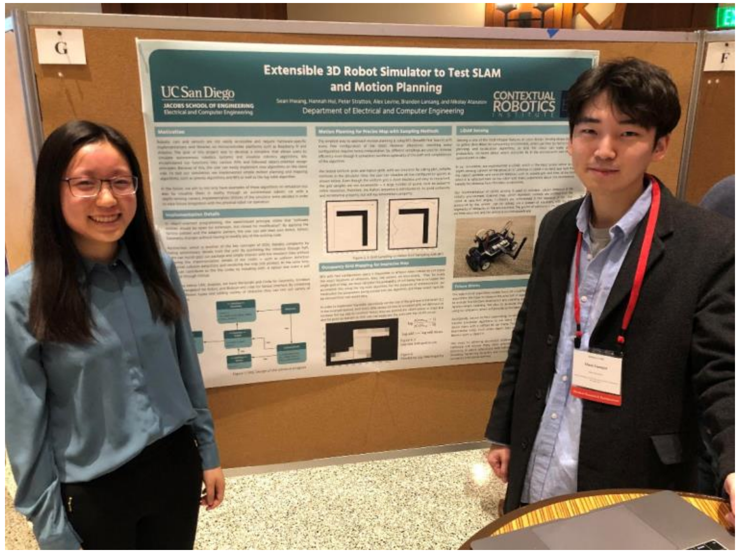
- Learned Lyapunov function for inverted pendulum (**NeurIPS, 2019**)
- **Critic** (obtain a neural Lyapunov function) – **Actor** (minimize Lie derivative) formulation for model free control (**ICRA, 2021**)
- Learned barrier function for model-free racecar simulator (**CoRL, 2021**)

Outreach and Research Initiation Activities

- Joint Seminars and Tutorial Series at SDSU and UCSD in 2020 and 2021:
  - **Seminar 1:** UAV terrain mapping
  - **Seminar 2:** optimization for sensor deployment
  - **Tutorial 1:** localization and mapping
  - **Tutorial 2:** robot motion planning
  - **Tutorial 3:** convex optimization
  - **Tutorial 4:** machine learning
  - **Open-source materials** and example implementations in pyBullet sim: https://github.com/ExistentialRobotics/robotics-workshop
- Research-initiation activities for undergraduate students:
  - 3 undergraduate students supported by NSF REU
  - 10+ undergrads supported by UCSD, SDSU outreach programs
  - 8 undergraduate poster presentations at SDSU Student Research Symposium and UCSD Research Expo







Undergraduate students presenting at the SDSU Student Research Symposium, 2020

Broader Impacts

- Real deployment plans negatively affected by COVID-19
- Established key connections and collaborations:
  - **Dr. Elsa Cleland**: post-fire vegetation regeneration and fuel analysis
  - **Dr. Frank Vernon** and **Dr. Hans-Werner Braun**: direct HPWREN sensor network that covers 20k square miles in Southern California
  - acquired permission to carry out UAV flight tests and sensor deployments at **Santa Margarita and Sky Oaks Ecological Reserves** in the San Diego area
  - connection with **San Diego County Fire Authority**