FRR: CAREER: Active Bayesian Inference for Collaborative Robot Mapping

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Intellectual Merit Plan:

- **Objective:** establish theory of active Bayesian inference and apply it to collaborative exploration and active mapping problems in robotics
- **Task A:** active Bayesian inference formulation as an optimal control problem for multi-robot sensing policy synthesis
- **Task B**: application of active Bayesian inference techniques to collaborative robot mapping

Education and Broader Impacts Plan:

- Demonstrate exploration and active mapping of unknown environments using a team of real ground and aerial robots
- Fundamental autonomy techniques developed in this project will impact various applications of mobile robots
- Develop **Robot Proving Grounds**, a suite of open-source implementations, examples, and tutorials of core robotics algorithms for localization, mapping, motion planning, and control, unified in an easy-to-use simulation environment
- Outreach and research activities for underrepresented K12 and undergrad students using RPG platform and support from UCSD outreach programs

Task A: Active Bayesian Inference

- Given **n** robots and planning horizon of **T** steps, choose control policies to minimize uncertainty about a target system (e.g., robot locations, map, any process of interest)
- Formulate a controlled variational inference problem and minimize an uncertainty measure of the posterior distribution over the space of sensing policies
- New **nonlinear Gaussian filtering** formulation allows efficient mean and covariance propagation with very general error-based motion and observation models
- Active SLAM over continuous trajectory and control: a covariance-feedback approach (**ACC'22**)
- Journal paper on active information acquisition in preparation

Task A: Distributed Bayesian Inference

- Cooperative estimation in a sensor network
- Developed a distributed Bayesian inference algorithm for continuous probability densities over time-varying directed graphs (**L-CSS'22** (submitted))
- Key ideas: **stochastic mirror descent** allows sequential/online variational inference, **KL divergence regularization of neighbor priors** to obtain a distributed formulation, proof of convergence for B-connected time-varying graphs using **large-deviations analysis**

Task B: New directional formulation for shape and surface modeling

- **Signed directional distance function** (SDDF) $h: \mathbb{R}^n \times S^{n-1} \mapsto \mathbb{R}$ of set $\mathcal{O} \subset \mathbb{R}^n$ measures signed distance from point $\boldsymbol{p} \in \mathbb{R}^n$ to set boundary $\partial\mathcal{O}$ in direction $\boldsymbol{\eta} \in S^{n-1}$: $h(\boldsymbol{p},\boldsymbol{\eta}) = d_{\boldsymbol{\eta}}(\boldsymbol{p},\partial\mathcal{O}) \coloneqq \min\{d \in \mathbb{R} \mid \boldsymbol{p} + d\boldsymbol{\eta} \in \partial\mathcal{O}\}$
- **SDDF gradient** with respect to $\boldsymbol{p}$ projected to $\boldsymbol{\eta}$ satisfies: $\nabla_{\boldsymbol{p}} h(\boldsymbol{p},\boldsymbol{\eta})^\top \boldsymbol{\eta} = -1$
- **SDDF structural property**: a function h is a valid SDDF if and only if $h(\boldsymbol{p},\boldsymbol{\eta}) = f\left(\boldsymbol{P}\boldsymbol{R}_{\eta}\boldsymbol{p},\boldsymbol{\eta}\right) - \boldsymbol{p}^\top\boldsymbol{\eta}$ for some $f: \mathbb{R}^{n-1} \times S^{n-1} \mapsto \mathbb{R}$, $\boldsymbol{P} = [\boldsymbol{I}\ \ \boldsymbol{0}]$, $\boldsymbol{R}_{\eta} \in SO(3)$
- **Major contribution**: neural network model for SDDF representation that guarantees valid SDDF by construction!
- Deep signed directional distance function for shape representation and view synthesis (**ECCV'22** (submitted))

Task B: Gradient-based optimization for active semantic mapping

- Log-odds mapping generalization to multiple classes with range and semantic observations; C++ implementation using an Octree data structure
- Closed-form lower bound on Shannon mutual information between multi-class Octree map and range-category observations using run-length encoding
- Allows rapid evaluation of many potential robot trajectories for autonomous exploration and active semantic mapping
- Differentiable formulation using Mutual information interpolation on a predefined grid of sensor views
- Semantic octree mapping and Shannon mutual information computation for robot exploration (**T-RO** (submitted))
- Active mapping via gradient ascent optimization of Shannon mutual information over continuous SE(3) trajectories (**IROS'22** (submitted))

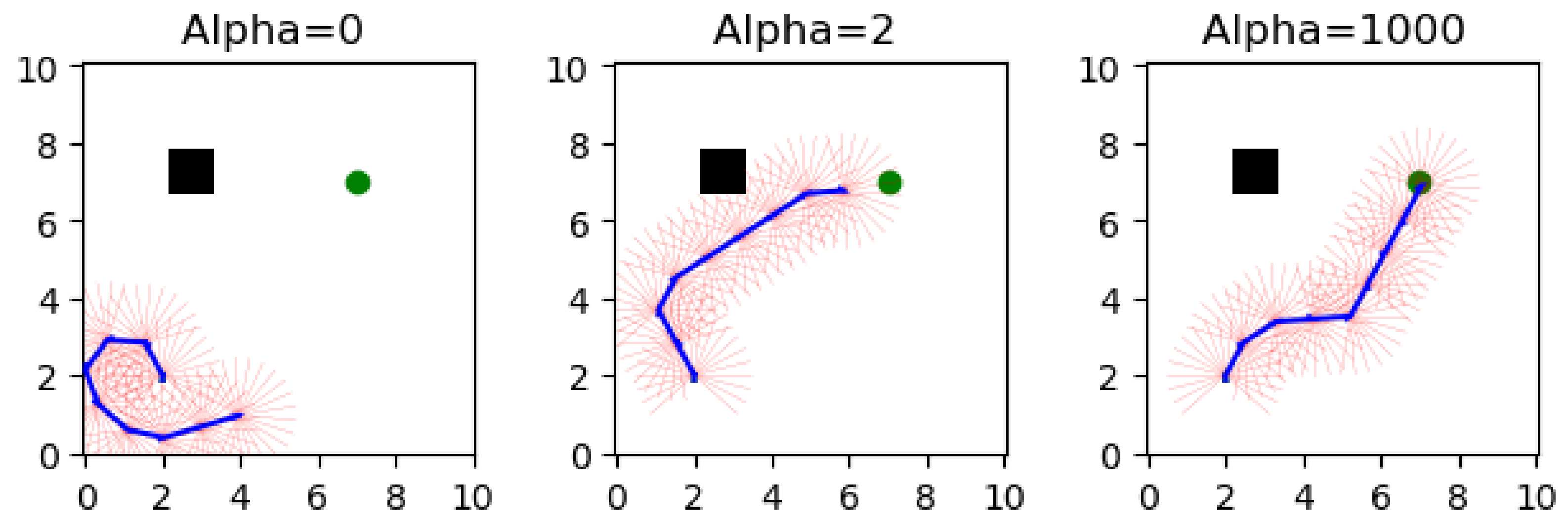


Figure: Active lidar localization in an occupancy grid map, trading off uncertainty minimization and distance to the goal

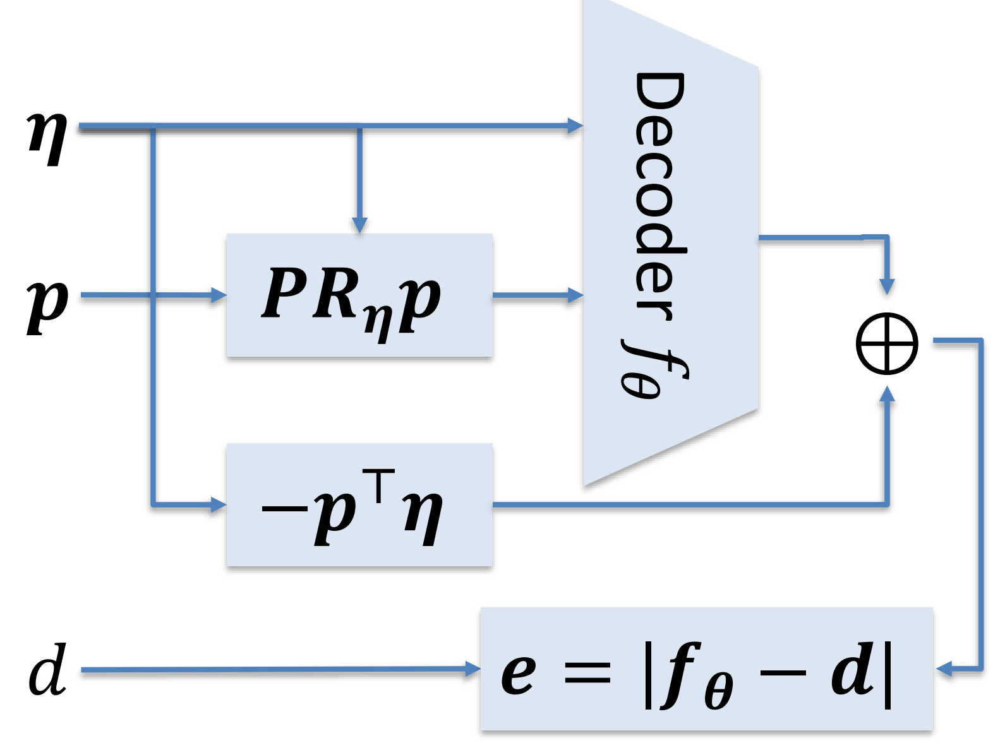
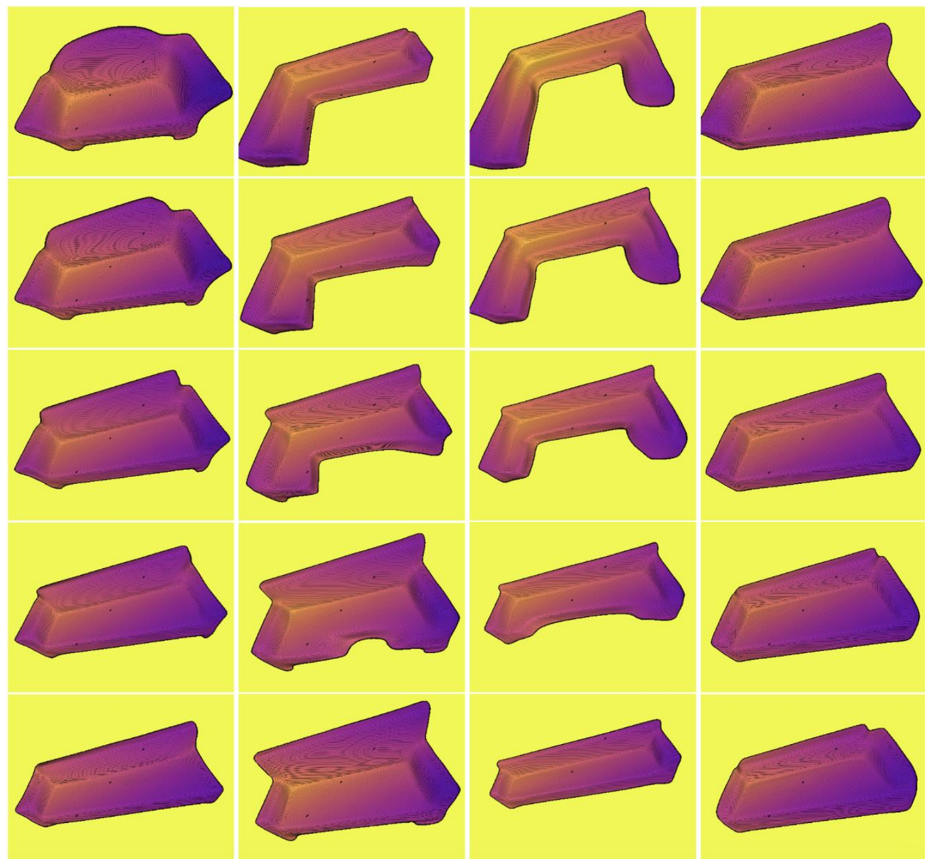
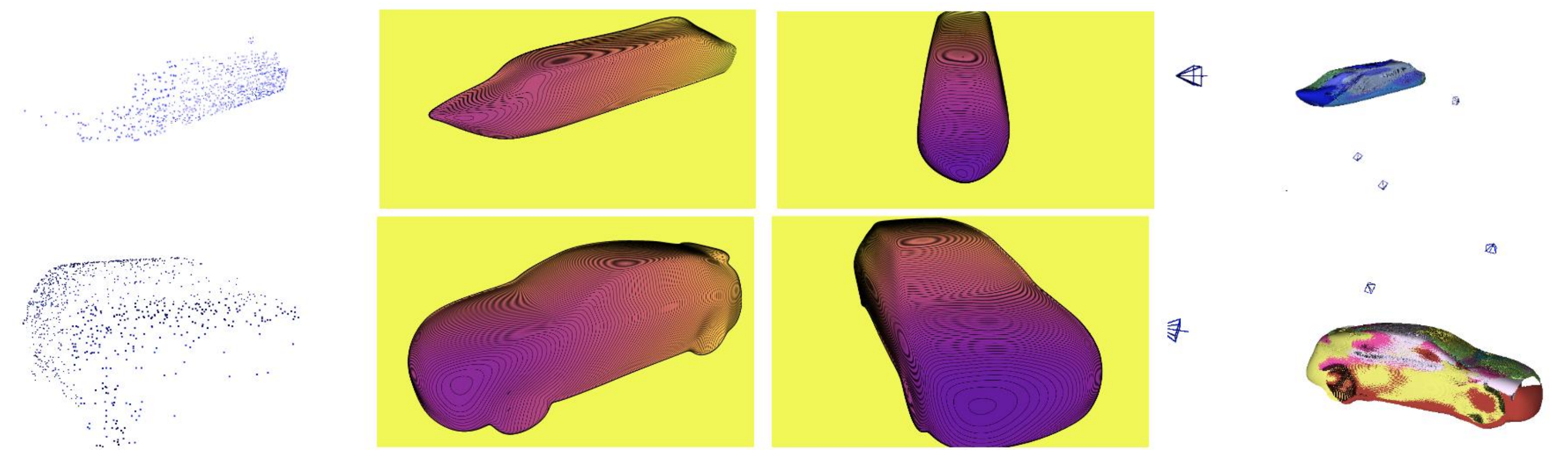


Figure: SDDF Neural Network





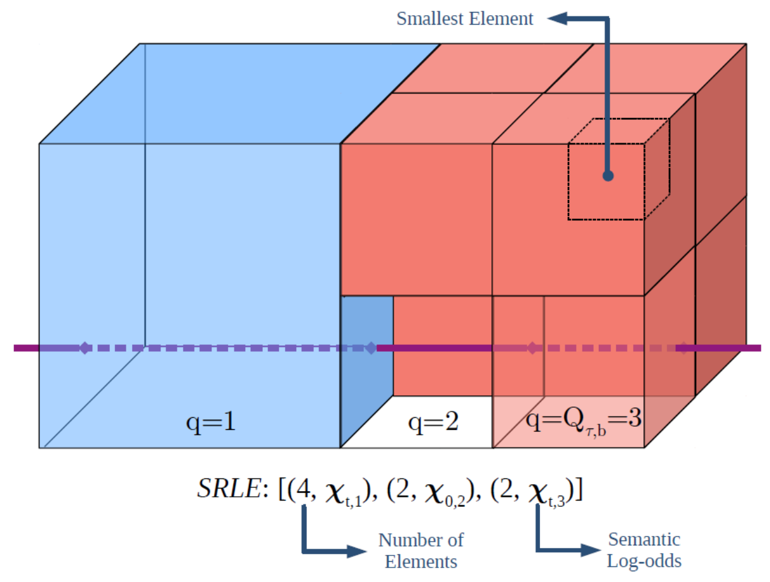


Figure: Semantic run-length encoding of multi-class log-odds in octree data structure

Figure: Active semantic octree mapping using closed-form approximation of mutual information between octree map and range-category measurements

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