CAREER: Game Theoretic Models for Robust Cyber-Physical Interactions: Inference and Design under Uncertainty

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(C1) Inferring Game Structure from Data

(RQ 1) How far ahead do agents plan?

(RQ 2) Can we infer hierarchies of influence among agents?

(RQ 3) How can we infer distributions of unknown structural parameters?

(C3) Nonparametric Process Uncertainty

(RQ 7) How can stochastic, hierarchical games be solved in parallel?

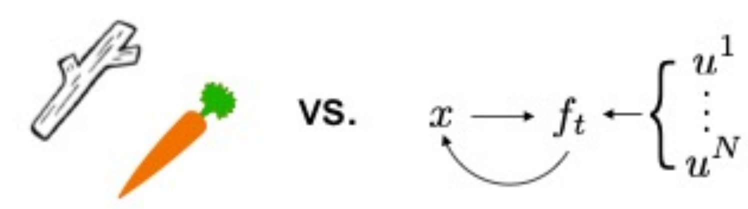
(RQ 8) When can scenario methods guarantee distributional robustness?

(RQ 9) Can we infer and design stochastic games?

(C2) Dynamic Mechanisms to Guide Equilibrium Outcomes

(RQ 4) Can *time-varying* incentives influence collaboration?

(RQ 5) How should operators influence game *dynamics*?



(RQ 6) When can CPS operators elicit unknown information?

(EO 1) Enrich existing engineering and robotics courses

Education Plan

(EO 2) New, cross-listed undergraduate course on modeling public transit policy

City of Austin's new public transit system

Key Challenges

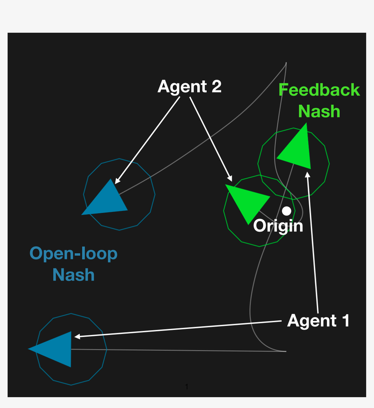
1. How can we *infer* the structure of strategic cyber-physical interactions? *(uncertain rationality and hierarchy)*
2. How and when can we *design* interaction structure to incentivize desired outcomes? *(beyond static, reactive mechanisms)*
3. How can we design algorithms to cope with unstructured model uncertainty? *(beyond typical Gaussian assumptions)*

Scientific Impact

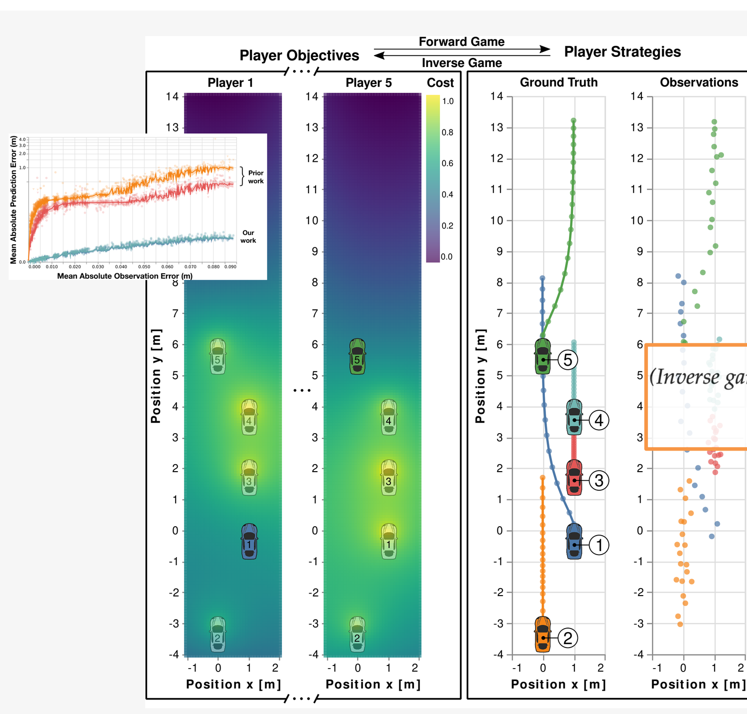
1. Theoretical framing which emphasizes the *dynamic, time-varying* nature of interactions as a first-class citizen.
2. Smooth, differentiable formulation of both inference and design problems to admit efficient solution methods.
3. Extension of computationally parallel scenario optimization approaches to cope with uncertainty in dynamic games.

Technical Approach

Key enabler: second-order methods for solving feedback Nash games



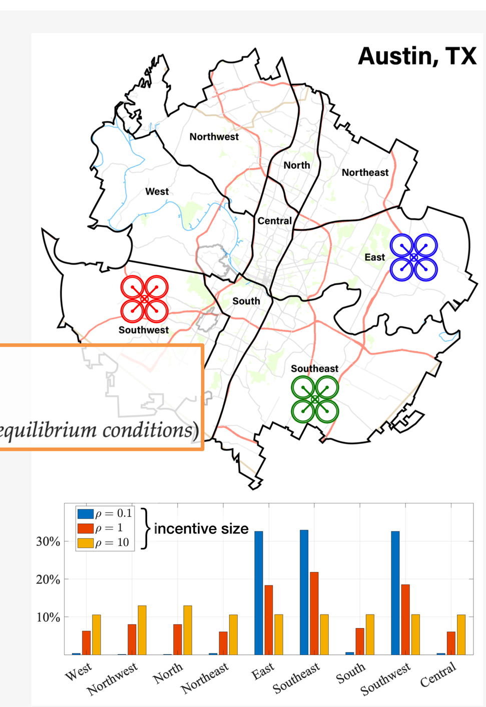
$$\textit{(Agent i's decision problem)} \quad \mathbf{u}^{i*} = \arg\min_{\mathbf{u}^i} \sum_{t=1}^{T} J^i(x_t, \mathbf{u}_t)$$
$$\text{subject to } x_{t+1} - f_t(x_t, \mathbf{u}_t) = 0, \forall t \in \{1, \dots, T-1\} \quad \textit{(game dynamics)}$$
$$x_1 - \hat{x} = 0. \quad \textit{(initial condition)}$$



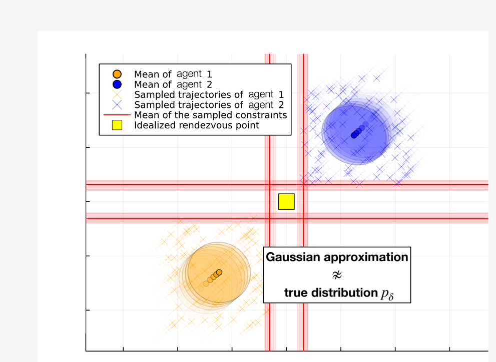
Idea 1
Inference and design as smooth *inverse games*

$$\textit{(Inverse game problem)} \quad \boldsymbol{\theta}^* = \arg\min_{\boldsymbol{\theta}, \mathbf{x}, \mathbf{u}} \sum_{t=1}^{T} \|y_t - h(x_t, \mathbf{u}_t)\|_2^2$$
$$\text{subject to } (\mathbf{x}, \mathbf{u}) \text{ a Nash solution for } \{J^i_{\theta^i}(\cdot)\}_{i=1}^N, \quad \textit{(equilibrium conditions)}$$

Unknown game parameters



Idea 2
Sampled approximations to stochastic games can be solved in parallel



Uncertainty!

$$\textit{(Agent i's stochastic problem)} \quad \mathbf{u}^{i*} = \arg\min_{\mathbf{u}^i} \mathbb{E}_{\delta \sim p_\delta}\left[\sum_{t=1}^{T} J^i(x_t, \mathbf{u}_t; \delta)\right]$$
$$\text{subject to } x_{t+1} - f_t(x_t, \mathbf{u}_t; \delta) = 0, \forall t \in \{1, \dots, T-1\} \quad \textit{(stochastic dynamics)}$$
$$x_1 - \hat{x} = 0. \quad \textit{(initial condition)}$$

$$\mathbf{u}^{i*} = \arg\min_{\mathbf{u}^i} \frac{1}{S} \sum_{j=1}^{S} \sum_{t=1}^{T} J^i(x_t, \mathbf{u}_t; \delta_j),$$

Broader Impacts

- New modeling tools for transit planners and regulators to guide policy decisions
- Reduced emissions, safer roads, more reliable air traffic management
- Extensions beyond transport, e.g., power distribution

Education and Outreach

- Expansion of existing course on game theory and multi-agent systems
- New undergraduate course on transportation modeling and policymaking

- Training REU students from UT and other MSIs

Award ID#: 2336840