Talking Vehicles: Cooperative Driving via Natural Language

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Motivation

How to create autonomous agents that can efficiently communicate with and collaborate with AI or human drivers?

- Line-of-sight sensing can be occluded, causing brittleness in data-driven autonomous driving. Vehicle-to-vehicle (V2V) communications are promising to enhance driving safety.
- uses cross-vehicle perception for vision-based cooperative driving, encoding sensor data into compact representations for transmission between vehicles over realistic wireless channels.
- Latent representations are only comprehensible by AI agents and is only reactive to situation. Natural language the one essential representation to facilitate such coordination with human drivers.

Problem Formulation

Research Questions:

1. What are effective messages to send?
2. How should received messages to be integrated into driving plans?

Partially Observable Stochastic Game $\langle \mathcal{I}, \mathcal{S}, \{\mathcal{O}_i\}, \{\mathcal{A}_i\}, \mathcal{P}, \{\mathcal{R}_i\}, \gamma \rangle$

Optimization Objectives

Total reward of focal population agents.
Definition 1 (focal population): A set of controllable agents that optimize their joint rewards given any background agents.

$$\max_{\{\pi_i\}_{i\in\mathcal{F}}} \mathbb{E}\left[\sum_{i\in\mathcal{F}} \sum_{t=0}^{t=\infty} R_i(s_t, \mathbf{a}_t) \middle| \{\pi_j\}_{j\notin\mathcal{F}, j\in\mathcal{I}}\right]$$

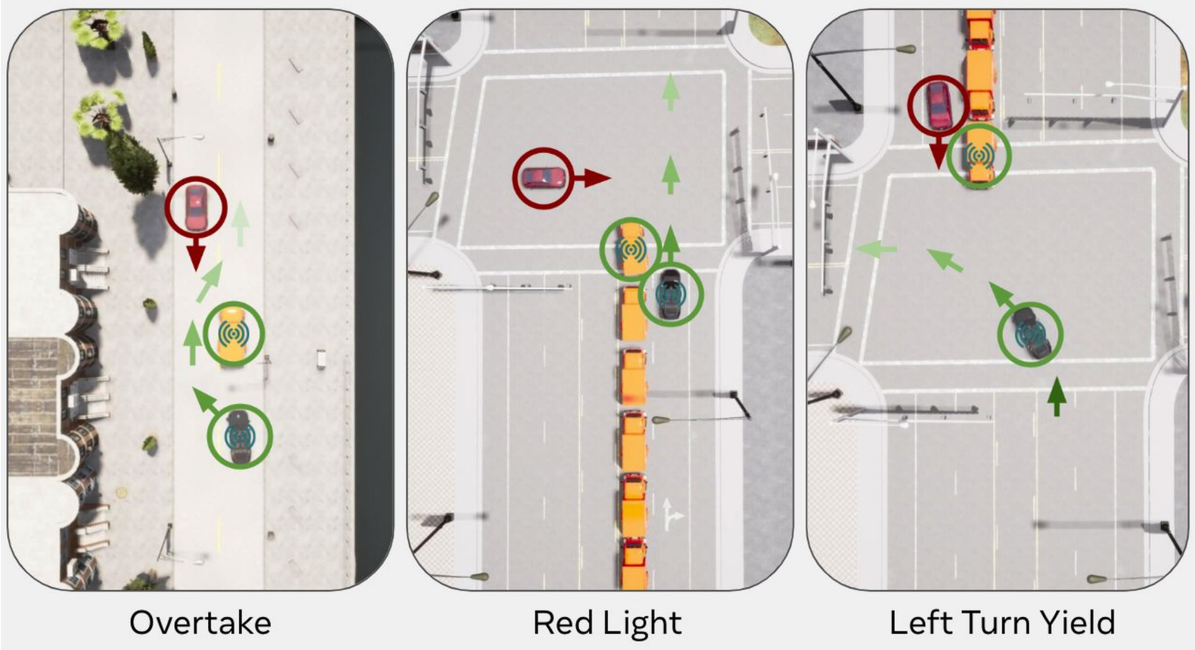
Policy Execution

$\pi_i(O_i, \{M_j\}_{j\in\mathcal{I}}) \rightarrow \mathcal{A}_i$
$\mathcal{A}_i = \langle \mathcal{M}_i, \mathcal{C}_i \rangle$

Joint action space of `<messages, control>`

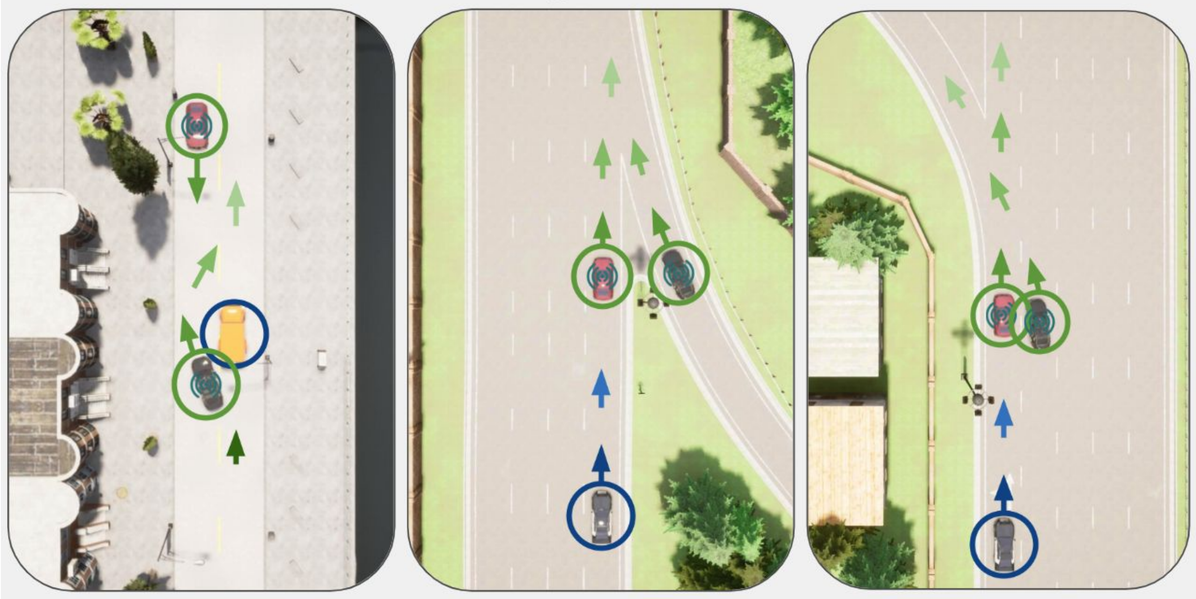
Scenarios

Cooperative Perception



Overtake · Red Light · Left Turn Yield

Negotiation

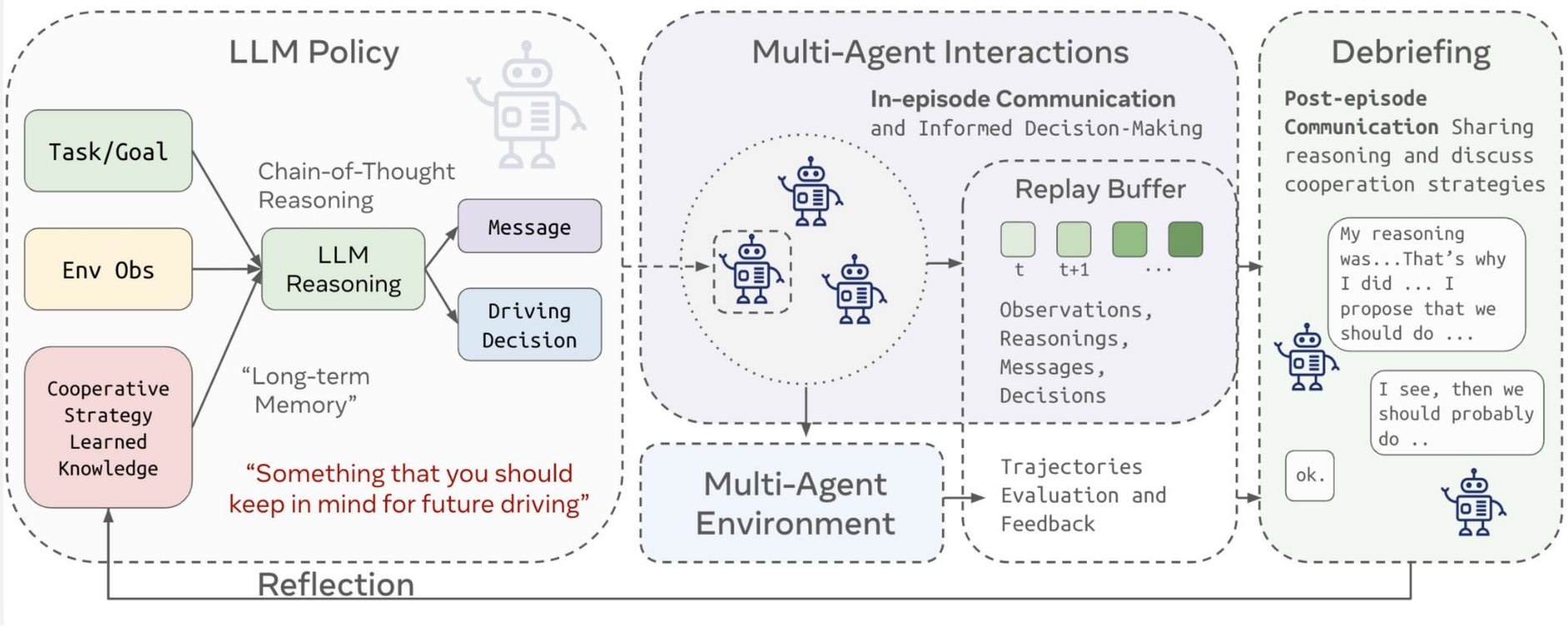


Overtake · Highway Merge · Highway Exit

Method: LLM Agent Framework +Debrief

Agent Policy
- In-context Knowledge
- Chain-of-Thought Reasoning

Agent Improvement
- Replay Buffer
  - natural language feedback
- Batch Context Sampling
  - heuristically assign more weights to state-action pairs that contributes to collision or stagnation
- Debrief
  - Joint Cooperation Strategy
  - Individual Knowledge
  - Resembles Centralized Training Decentralized Learning (CTDE) algorithms



Experiments

Quantitative
- Communication does not guarantee collaboration in zero-shot interactions
- Decentralized reflection and correction with RAG memory reduce collisions.
- Centralized debriefing enhances coordination more than decentralized reflection.
- The potential of natural language communication for multi-agent coordination.

Qualitative
- Message generated are understandable by humans
- Learned coordinated strategies make sense

Discussion
- Inference speed, more agents, ad-hoc teamwork, VLM…

Results

Method \ Scenario			Overtake (Negotiation)			Highway Merge			Highway Exit		
Name	LLM	Comm	R ↑	CR ↓	SR ↑	R ↑	CR ↓	SR ↑	R ↑	CR ↓	SR ↑
Zero-shot (Silent)	Yes	No	-0.13	55.0	41.7	-0.87	93.3	6.7	-0.53	63.3	36.5
+Reflection (Silent)	Yes	No	0.80	3.0	83.3	-0.37	68.3	31.7	0.20	40.0	60.0
+Correction+RAG (Silent)	Yes	No	0.00	50.0	50.0	0.03	48.3	51.7	-0.16	58.3	41.7
Zero-shot (Comm)	Yes	Yes	0.53	23.3	76.5	-1.00	100.0	0.0	-0.60	65.0	35.0
+Reflection (Comm)	Yes	Yes	0.73	11.7	85.0	0.53	23.3	76.7	0.32	33.3	65.0
+Correction+RAG (Comm)	Yes	Yes	0.83	6.7	90.0	-0.07	53.3	46.7	-0.16	58.3	41.7
+Debrief (Comm)	Yes	Yes	**1.00**	**0.0**	**100.0**	**1.00**	**0.0**	**100.0**	**0.63**	**10.0**	**73.3**

Method \ Scenario			Overtake (Perception)			Red Light			Left Turn		
Name	LLM	Comm	R ↑	CR ↓	SR ↑	R ↑	CR ↓	SR ↑	R ↑	CR ↓	SR ↑
Zero-shot (Silent)	Yes	No	-0.87	93.3	6.7	-0.87	93.3	6.7	-0.93	96.7	3.3
+Reflection (Silent)	Yes	No	-0.26	36.7	10.0	-0.87	93.3	6.7	-0.27	63.3	36.7
+Correction+RAG (Silent)	Yes	No	0.07	33.3	40.0	-0.73	86.7	13.3	0.20	40.0	60.0
Zero-shot (Comm)	Yes	Yes	-0.46	73.3	26.7	-0.33	66.7	33.3	-1.00	100.0	0.0
+Reflection (Comm)	Yes	Yes	0.40	30.0	70.0	0.07	10.0	26.7	**0.60**	**20.0**	**80.0**
+Correction+RAG (Comm)	Yes	Yes	**0.70**	**6.7**	76.7	0.73	13.3	87.7	-0.60	76.7	16.7
+Debrief (Comm)	Yes	Yes	0.63	16.7	**80.0**	**1.00**	**0.0**	**100.0**	**0.60**	**20.0**	**80.0**
Coopernaut (Comm)	No	Yes	1.00	0.0	100.0	0.97	0.0	96.7	1.00	0.0	100.0