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Integration of Large Language Models into Multi-Agent Simulations: Swarm Intelligence and Emergent Behavior

Jimenez Romero, C.¹, Manos T.¹, Blum, C.², Yegenoglu, A.³

¹ETIS Lab, ENSEA, CNRS, UMR8051, CY Cergy-Paris University

²Artificial Intelligence Research Institute (IIIA), Spanish National Research Council (CSIC)

³RWTH Aachen University

Introduction

The convergence of artificial intelligence and complex system modeling has opened new opportunities for exploring swarm intelligence and emergent behaviors. Traditional multi-agent simulations rely on predefined rule sets, limiting adaptability. By integrating Large Language Models (LLMs), we shift from rigid systems to dynamic, knowledge-driven interactions. This work leverages LLMs to guide agent behavior in real-time, offering insights into self-organization and collective intelligence. Using the NetLogo simulation environment, we explore ant colony foraging and bird flocking, demonstrating how LLMs can facilitate emergent behaviors inspired by natural phenomena.

Methodology

Experiment 1: Ant Colony Foraging Simulation

- **Setup:** The simulation models ants foraging for food in a two-dimensional environment using structured prompts generated by ChatGPT-4.
- **LLM Integration:** ChatGPT-4 processes environment feedback to dictate ant behaviors like moving forward, picking up food, and following pheromone trails.
- **Prompt Design:** Zero-shot prompts ensure each agent response is stateless, relying solely on real-time inputs.



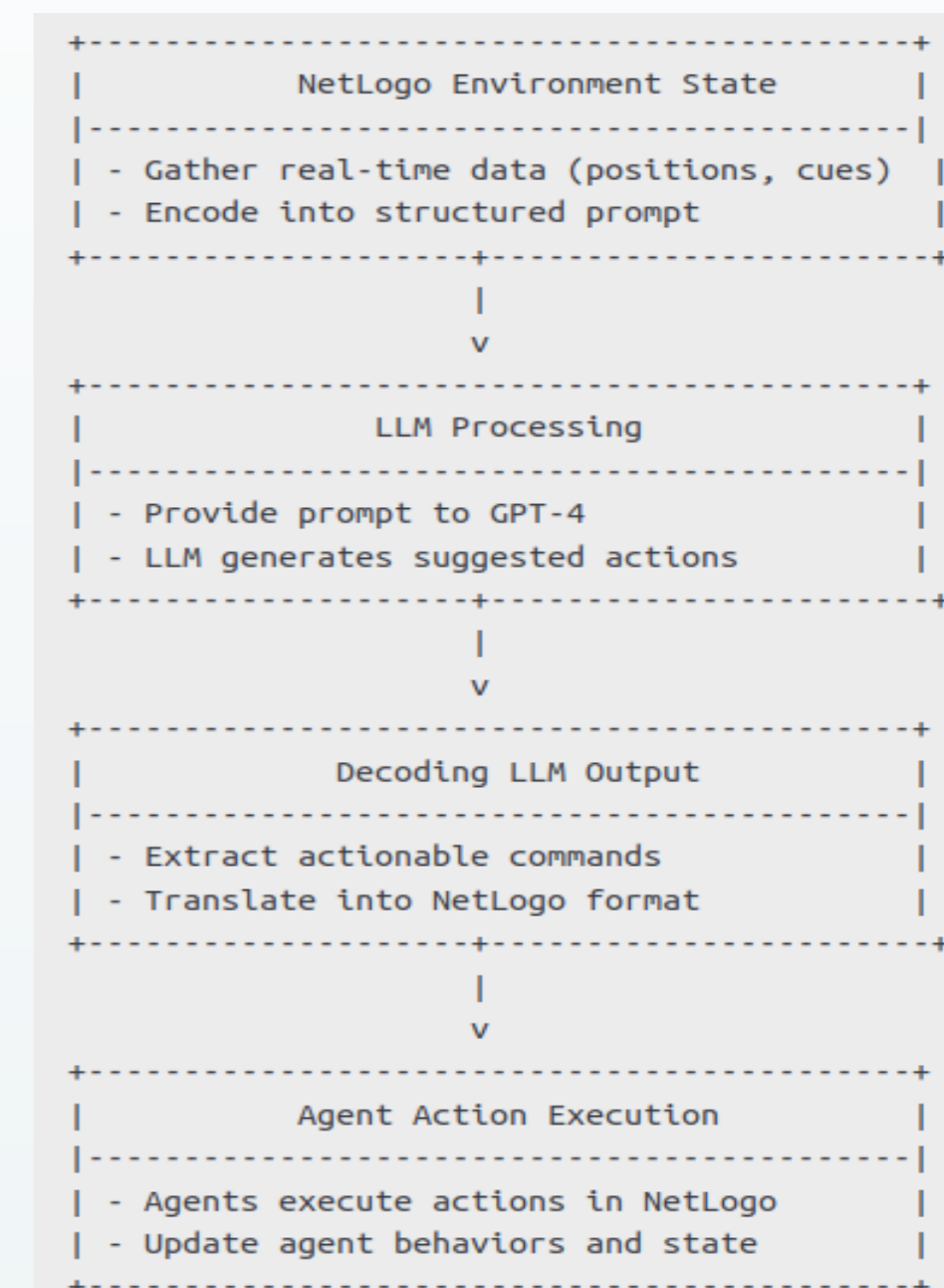
Experiment 2: Bird Flocking Simulation

- **Setup:** Birds move in a two-dimensional airspace, demonstrating alignment, cohesion, and separation dynamics. Most of the bird agents were rule-based, with only a subset controlled by LLM-generated prompts. The rule-based birds interacted with LLM-driven agents, creating a mixed population that allowed us to observe the influence of LLMs within a predominantly rule-based system.
- **LLM Integration:** Prompts guide birds to align with neighbors, avoid collisions, and maintain cohesion. The LLM-driven birds utilized GPT-4's understanding of flocking principles to interact effectively with both rule-based and other LLM-driven agents.
- **Prompt Design:** Prompts leverage GPT-4's understanding of flocking dynamics, using parameters like heading alignment and separation distance. This allowed for consistent flocking behavior across both rule-based and LLM-driven birds.



Workflow Summary

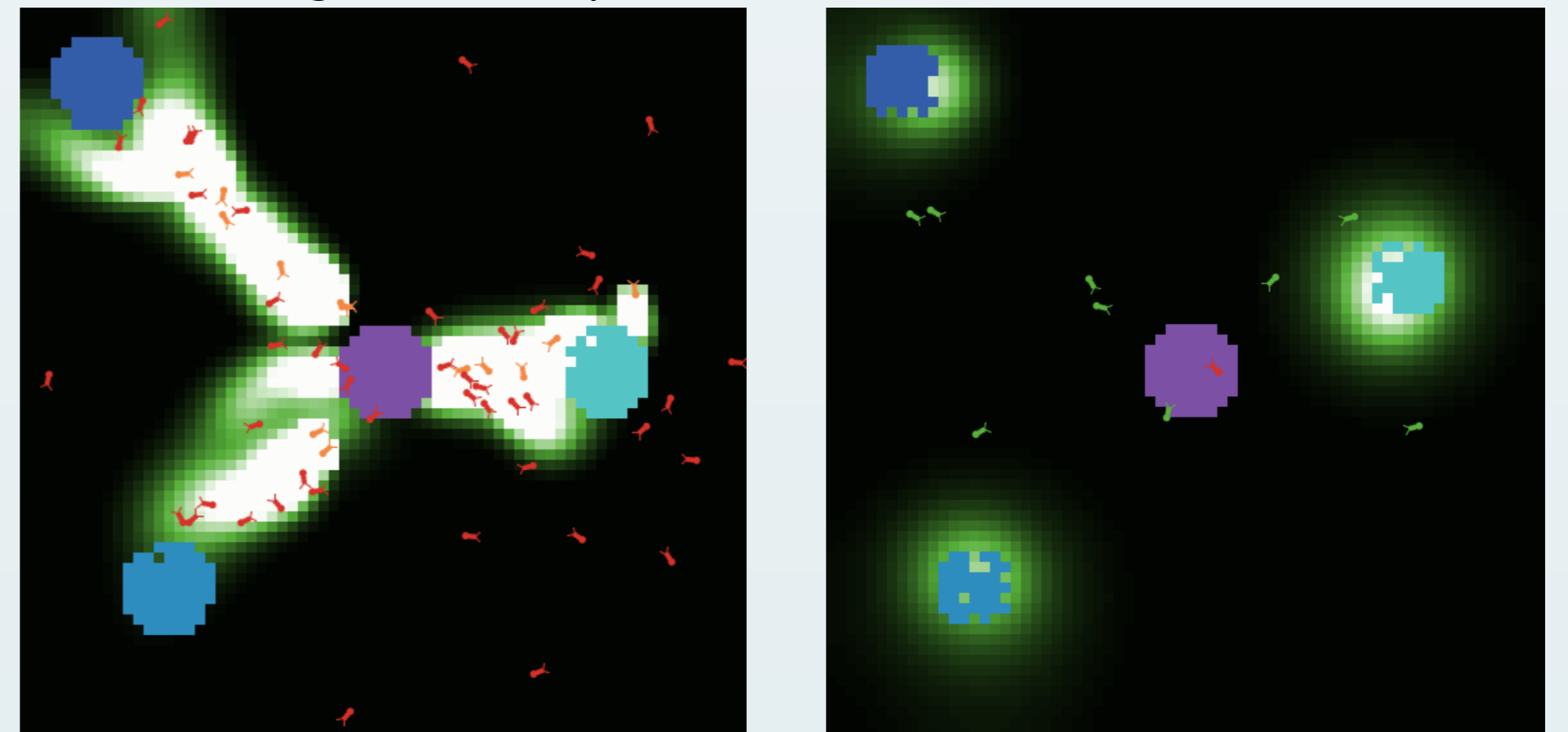
- I. Environment Encoding: Real-time data from the NetLogo environment is encoded into structured prompts for the LLM. This includes agent positions, pheromone levels, and neighborhood interactions.
- II. LLM Processing: The structured prompt is provided to GPT-4, which generates suggested actions for the agents based on its understanding of the environment.
- III. Decoding LLM Output: The LLM-generated response is decoded into actionable commands and translated into NetLogo-compatible instructions.
- IV. Agent Action Execution: NetLogo agents execute the commands, updating their behaviors and states, thereby influencing the environment for subsequent iterations.



Results

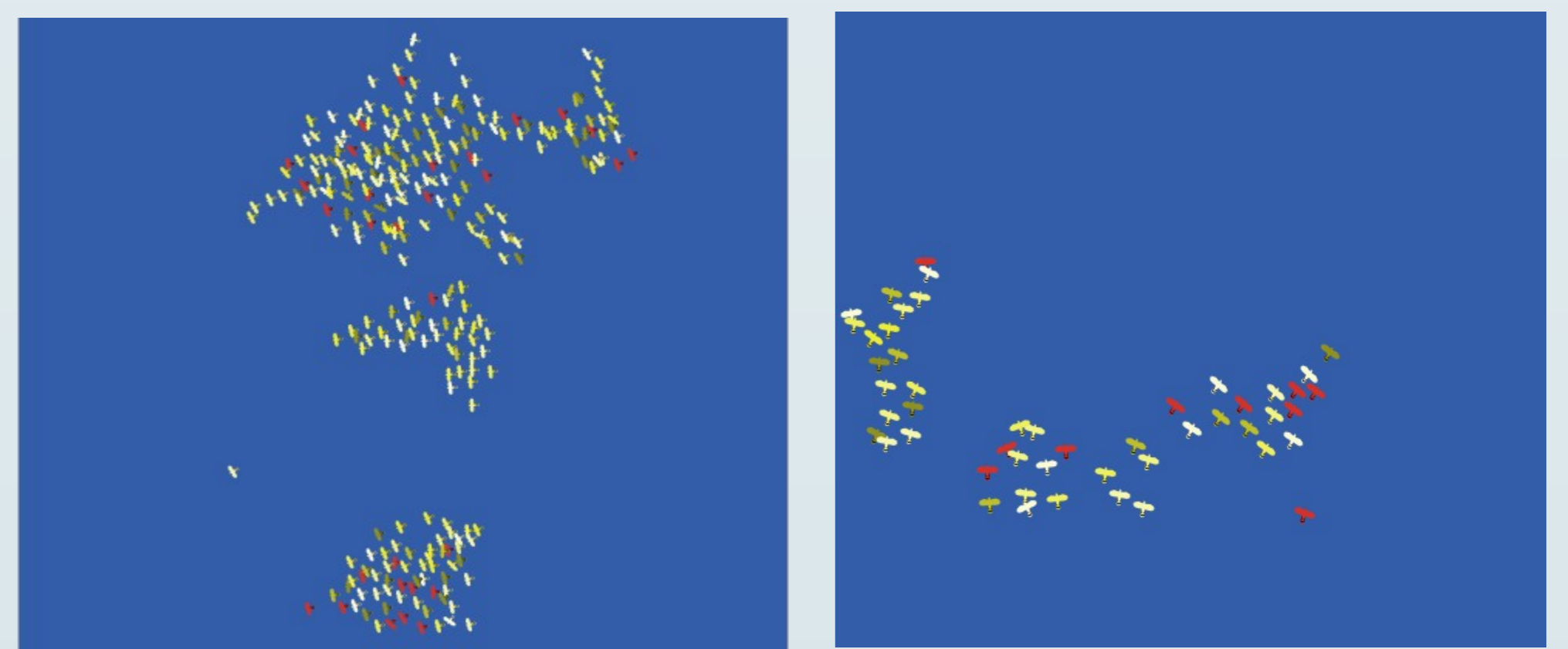
Ant Colony Foraging

- **Adherence to Prompts:** Ants closely followed instructions, leading to efficient foraging and consistent pheromone trails.
- **Foraging Success:** Efficiency was measured by food collected over time, showing effective optimization of retrieval.



Bird Flocking

Birds exhibited stable dynamics, with consistent alignment, cohesion, and separation across the population. Rule-based birds and LLM-driven birds interacted seamlessly, demonstrating that the implicit knowledge of flocking dynamics within LLMs allowed them to integrate effectively into the flock. This resulted in cohesive flock formations, even when the majority of the birds were rule-based.



Conclusion

Integrating LLMs with agent-based simulations offers a new approach to exploring swarm intelligence and emergent behaviors. This study shows that LLMs can influence agent behaviors to achieve self-organization and collective intelligence, even when integrated with predominantly rule-based agents. The seamless interaction between rule-based and LLM-driven agents in the bird flocking experiment highlights the robustness of LLMs in contributing to emergent behaviors, paving the way for more adaptive systems capable of modeling complex, real-world swarm behaviors.