Motility-Induced Phase Separation and chemotaxis as a Mechanism for Efficient Swarm Payload Transport

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ABSTRACT : This project presents an agent-based model that investigates collective payload transport in a toroidal arena. Each Agent follows a Vicsek alignment rule augmented by weak chemotactic signals emitted by payload and target. Motility-induced phase separation emerges as the driving mechanism: once density, scent bias, interaction radius and noise exceed threshold values, clusters self-organize to carry the payload towards the target.

RESEARCH QUESTION

How do agent simulation parameters such as scent bias, interaction radius, noise, and agent density interact to trigger motility induced phase separation and also demonstrate reliable payload delivery in a toroidal arena?

LITERATURE REVIEW

Emergence shows how simple local rules can lead to macroscopic behaviour. Onsager's exact 2-D Ising solution (1944)**[1]** demonstrated that local spin interactions generate collective macroscopic behavior, indirectly setting the foundation for the field of emergence. The landmark Vicsek model (1995)**[2]** translated the idea to motion: fixed speed agents average neighbor headings with the addition of noise and suddenly flock when noise reaches a threshold. Examples of biological emergence are plentiful, spanning the microscopic world, insect colonies, and even the complex social behaviors of large animals**[3]**. This project includes a property of active matter observed in Fire-ant where ant rafts exhibit motility-induced phase(MIPS) separation governed by density and activity cycles **[4]**. In synthetic active matter Quincke rotation provokes Janus colloids to self-polarize under an electric field, passing from anisotropic gas to polar liquid without sensing**[5]** Although the local couplings differs (electric field vs. social cues), both ants and colloids demonstrate the same principle: simple local alignment plus a scalar control parameter (density, field strength) can switch the collective between an isotropic state to solid-like phase.

Robotics research now makes use of biological and active matter findings. The Kilobot swarm self-assembles 2-D shapes by locally estimating IR intensity seeded by "leader" bots in the swarm, achieving programable assembly without centralization**[6]**. More recently, vision dependent robots and micro-drones have demonstrated collective gradient ascent without explicit gradient sensors, in this case cohesion is maintained by modulating speed or desired spacing such that the swarm drift up the scalar field.**[7]**
Most prior robot swarms either (i) flock with no global objective (pure Vicsek) or (ii) rely on pre-placed gradient sources that strongly dominate alignment. This project NetLogo model focuses on a stochastic middle ground: each agent performs a Vicsek update to preserve polarization, then includes a small steering "nudge" term proportional to the local difference between "payload scent" and "target scent". This retains the rich phase behavior of Vicsek dynamics while also assigning the swarm a goal. Motility induced phase separation (MIPS) as seen in Fire ants clusters**[8]** is also included in the agents behavior and lets clusters push the "payload" collectively while also preventing jamming when navigating a random obstacle course.

METHODOLOGY

A Netlogo swarm model was developed to combine three local rules:

- Chemotactic scent-gradient $\theta_i \longleftarrow \theta_i + k_s \mathbf{1}[s_{\max,i} > s_{\text{here},i}] (\theta_{\text{scent},i} - \theta_i)$
- Vicsek alignment + noise: $\theta_i^{t+1} = \theta_i^t + k_s(\theta_{\text{scent},i}^t - \theta_i^t) + \eta_i^t(\theta_{\text{align},i}^t - \theta_i^t)$
- Density triggered (MIPS): $v_i = \begin{cases} v_0, & \rho_i < \rho_c, \\ \beta v_0, & \rho_i \geq \rho_c, \end{cases}$

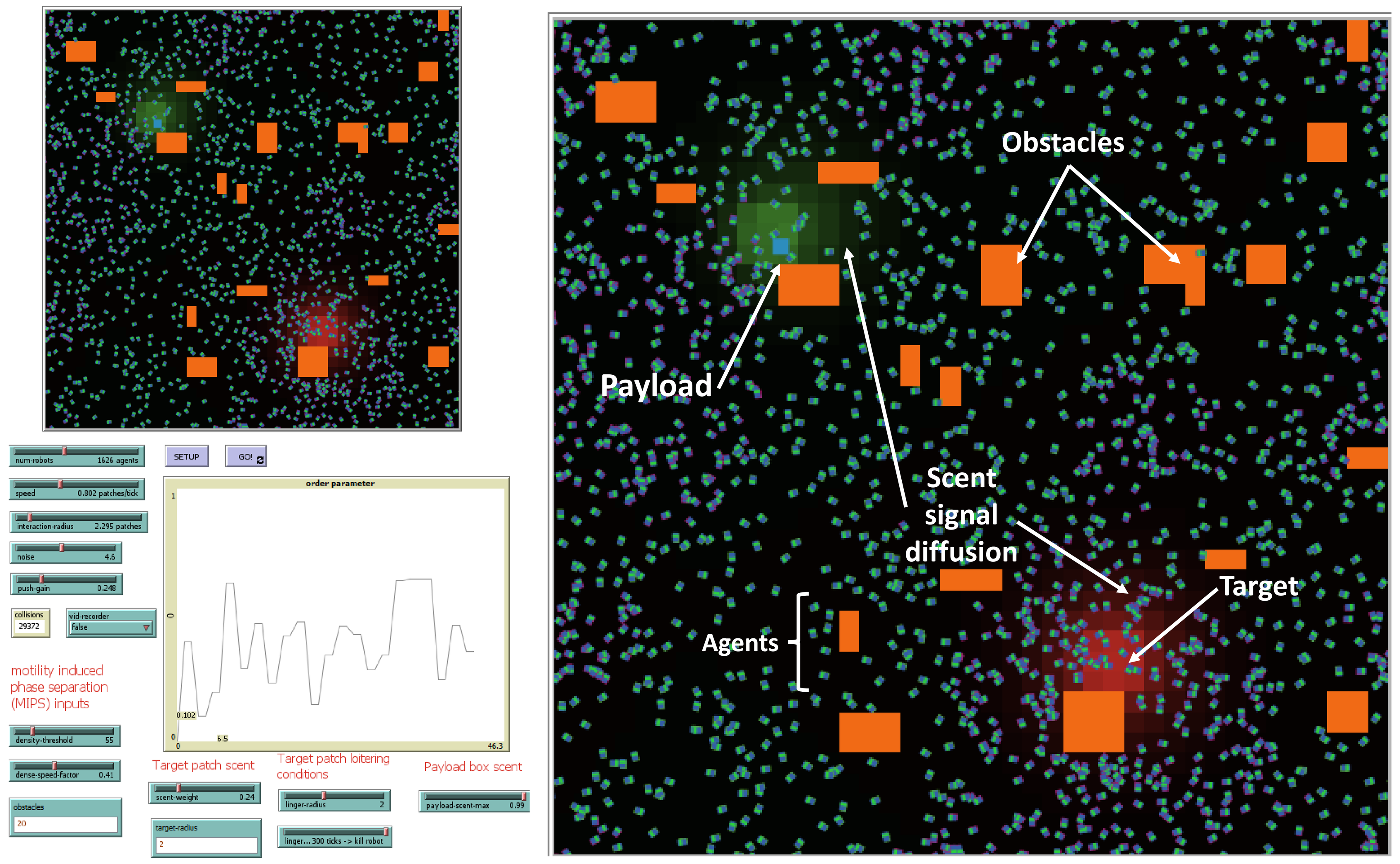

Figure 3. Swarm simulation GUI and sample run:
Snapshot of NetLogo software during a run: blue dots represent agents executing the rule set, orange blocks are fixed, randomly placed obstacles. the payload (blue box) emits a green diffusive scent, and the target (red box) emits a red scent. The graph represents a global polarization measurement.

RESULTS & DATA

Fig 1A.

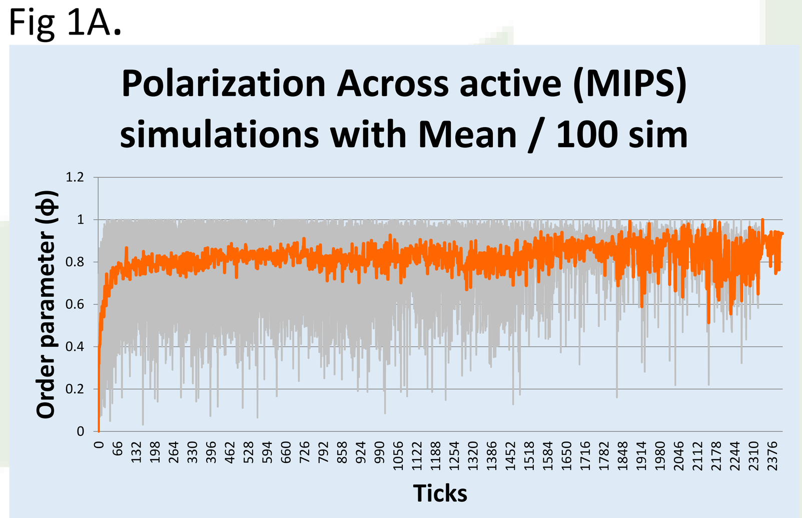

Fig 1B.

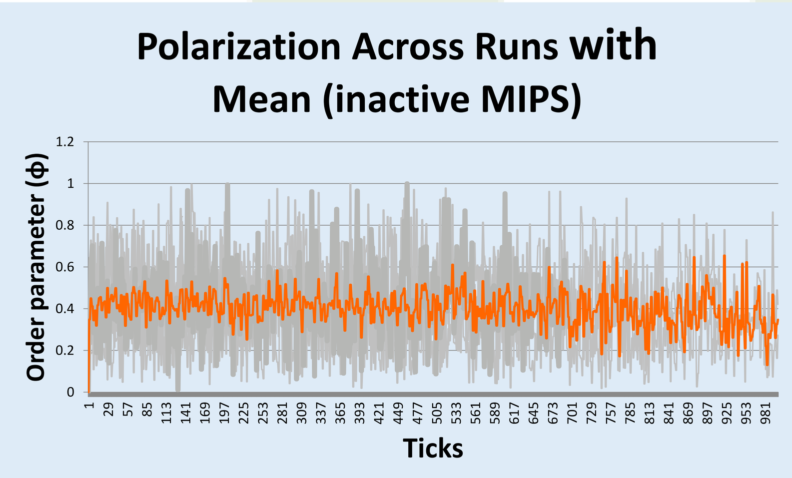

Figure 1 Collective alignment (order parameter ϕ) with and without MIPS activation.
(1A) Active-MIPS runs: individual trajectories (grey) converge toward high polarization, and the mean (orange) rises steadily, and remains stable, indicating rapid global alignment.
(1B) Inactive-MIPS runs: trajectories remain noisy and low, and the mean order parameter stays near 0.3–0.5 , indicating that the swarm never develops sustained collective orientation.

The model is designed as a 20 × 20 patch arena with top and bottom edges wrapped such that an agent leaves through the top and renters immediately the bottom.
This configuration was chosen due to the similarity of physical experiments done with Janus colloids in toroidal enclosures with the distinction that this model expresses a surface instead of a volume .
Agents are initially placed at random and respond to user defined inputs (interaction radius, speed, and noise, etc).

Each run assigns obstacles, the payload, and the target locations. The payload and target emit a weak chemotactic signal that slightly biases agent headings toward them, but motion is overall dominated by simple Vicsek alignment.

To explore parameter space, a coarse sweep of approximately 435,000 simulations was ran in BehaviorSpace to identify effective parameter sets. Then a narrower sweep of 1,000 simulations was performed focused on the most promising region to isolate the best parameter combinations.

Fig 2A.

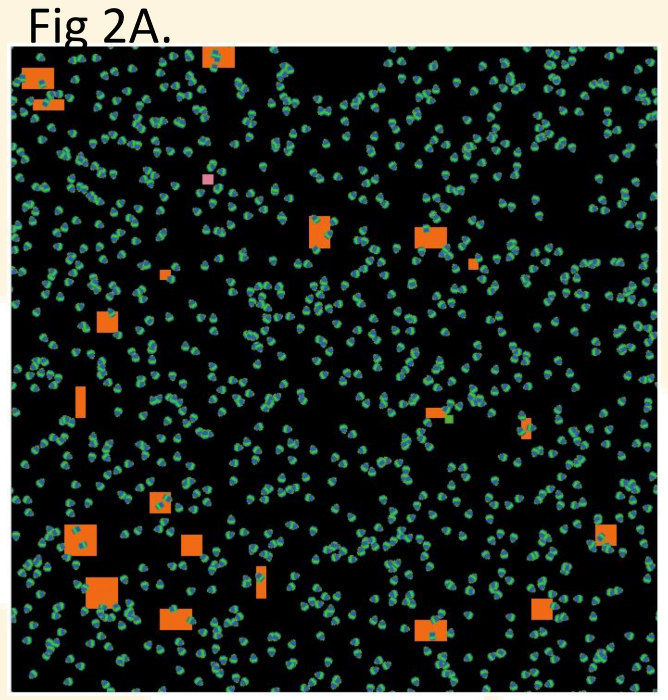

Fig 2B.

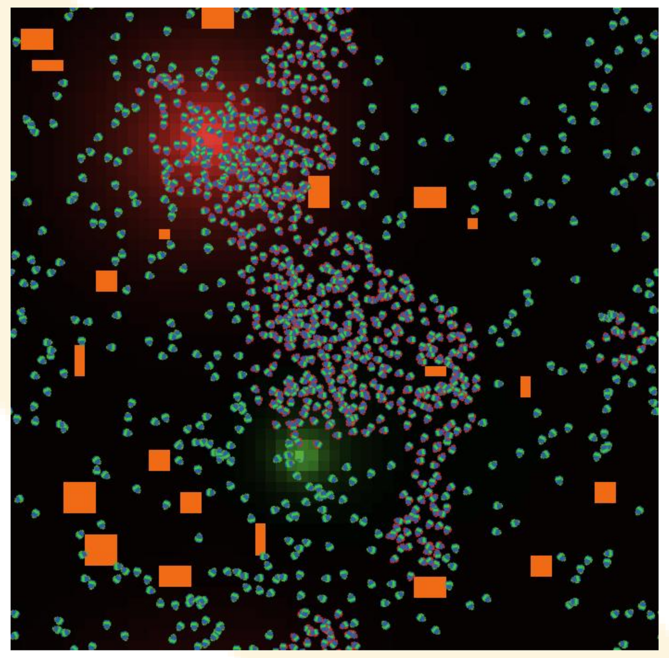

Fig 2C.

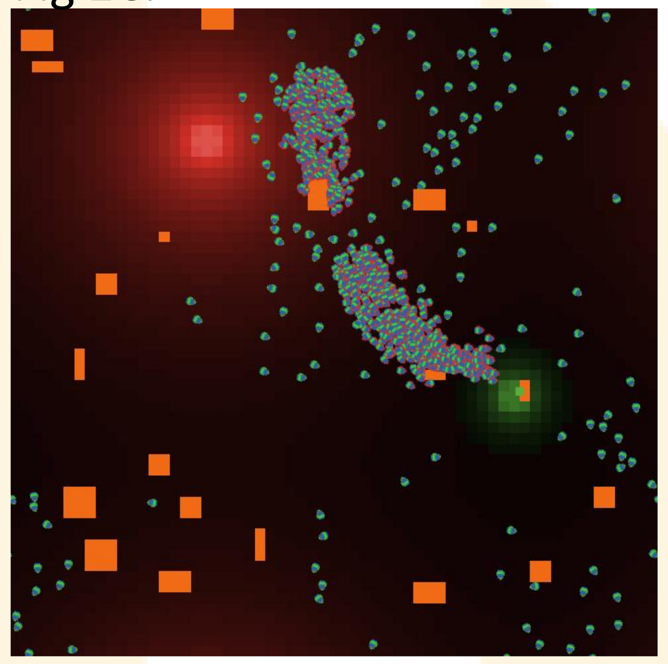

Fig 2D.

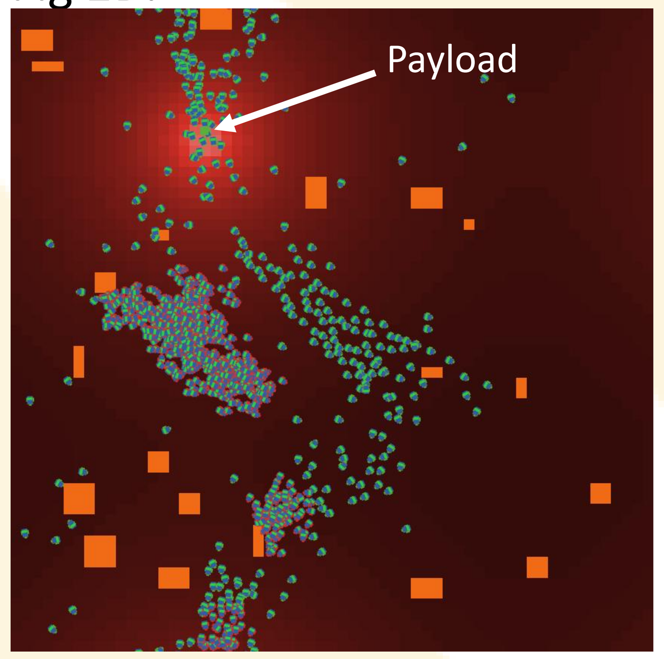

Figure 2 Motility-induced phase separation (MIPS) drives payload transport.
(2A) Initially, agents (green) are uniformly dispersed among static obstacles (orange).
(2B) MIPS triggers dense, polarity-aligned clusters that nucleate around the chemotactic signals (green = payload, red = target).
(2C) Cohesive flocks form a stream linking payload to target.
(2D) The leading cluster escorts and ultimately deposits the payload at the target zone, completing delivery.

DISCUSSION/CONCLUSIONS

Comparing runs with active versus suppressed MIPS suggests that motility induced phase separation plays a critical role in successful payload delivery. Vicsek alignment by itself can deliver the payload, but it does so by a stochastic clustering. When MIPS works together with weak chemotactic signals the agents form polarized flocs almost immediately, yielding higher success rates and shorter completion times.
Moderate noise was observed to be necessary for Vicsek alignment and MIPS, yet at the same time noise had critical boundaries which once surpassed generated instability and did not allow for flocking, resembling an isotropic gas. The effective set of parameters contains a narrow, noise dependent "sweet-spot" where Vicsek alignment, MIPS and chemotaxis act effectively

Future work could replace exhaustive parameter sweeps with machine learning to predict effective regions, or embed small neural networks as the agents control mechanism to develop more adaptative policies and discover new delivery strategies.

- Netlogo model and raw data available by scanning the QR code →

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