Deadlock and Noise in Self-Organized Aggregation Without Computation

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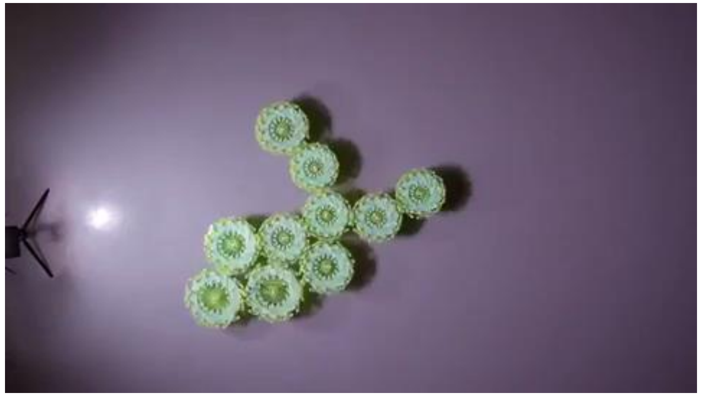
Minimally Capable Swarm Robotics

Minimizing the capabilities of individual robots allows these distributed systems to remain feasible and effective at smaller scales (e.g., microscale, nanoscale).

"Catoms"
PB 2018

"Kilobots"
RCN 2014

"M-Blocks"
RGR 2013

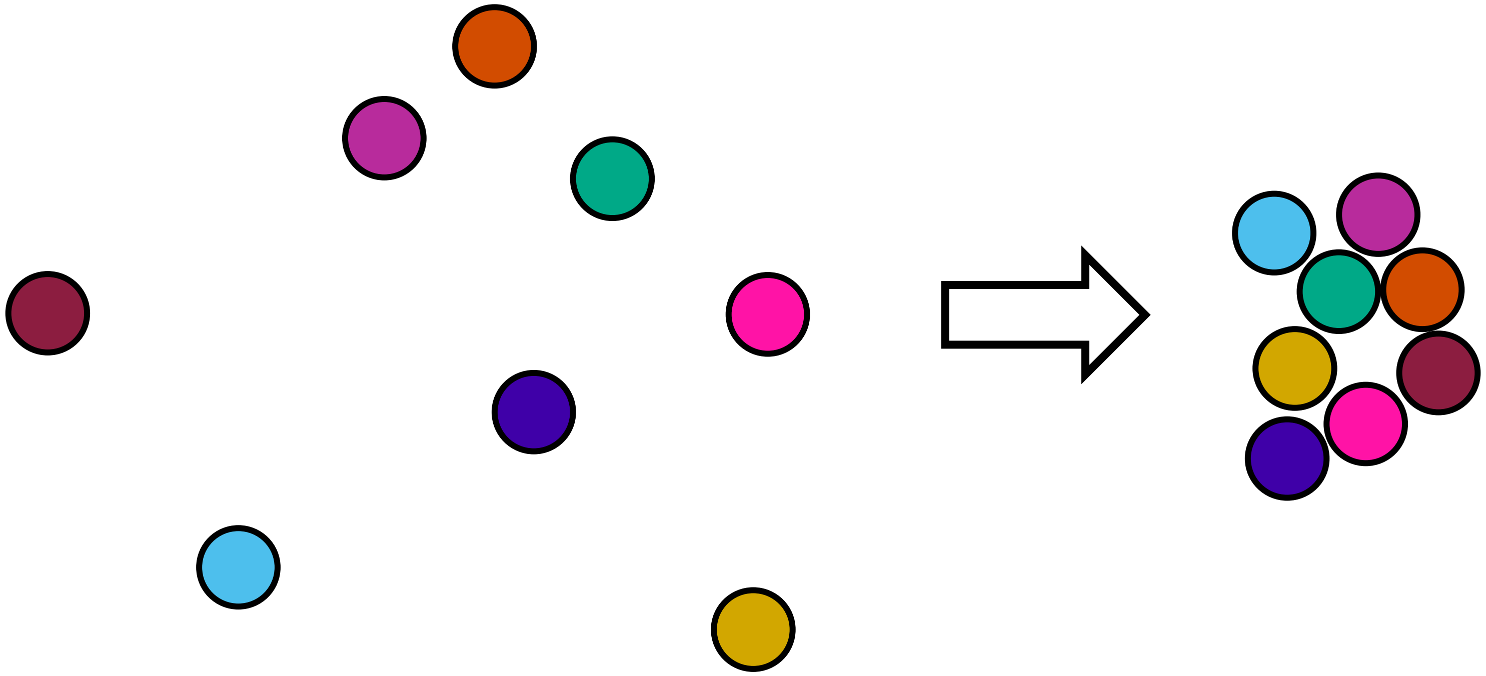


"Particle Robots"
LBBCRHRL 2019

Swarm Aggregation

Given n robots in arbitrary initial positions in the 2D plane, define a distributed controller for each individual robot such that all n robots eventually form a single connected component that is as compact as possible.

This is a well-studied problem in swarm robotics, mobile robots, and programmable matter.



The Gauci et al. Algorithm

Though many solutions exist, researchers worked to further minimize the capabilities of the individual robots required to achieve aggregation.

In 2014, Gauci et al. devised a solution in which each robot has only a single binary line-of-sight sensor. The robots do not have any persistent memory and do not perform any arithmetic computations.

In their formulation:

1. Let $v_\ell, v_r \in [-1,1]$ denote the normalized left and right wheel velocities.
2. Let $I = 1$ if the line of sight sensor sees another robot; otherwise, let $I = 0$.
3. Drive with $v_\ell = v_{\ell I}$ and $v_r = v_{rI}$.

Thus, the driving behavior of the robots is defined entirely by the controller:

$$\boldsymbol{x} = (v_{\ell 0}, v_{r0}, v_{\ell 1}, v_{r1}) \in [-1,1]^4.$$

The Gauci et al. Algorithm

Using grid search, they determined the highest performant controller was:

$$\boldsymbol{x}^* = (-0.7, -1, 1, -1)$$

Letting R be the radius around $\boldsymbol{c}$ and ω the angular speed, this means:

- If no robot is seen, rotate around $\boldsymbol{c}$ with $R = 14.45 \text{ cm}$ and $\omega = -0.75 \text{ rad/s}$.
- Otherwise, rotate around $\boldsymbol{c}$ with $R = 0 \text{ cm}$ and $\omega = -5.02 \text{ rad/s}$.

What does that mean for the algorithm?

1. If no robot is seen, rotate clockwise around $\boldsymbol{c}$.
2. Otherwise, if a robot is seen, rotate clockwise in place.

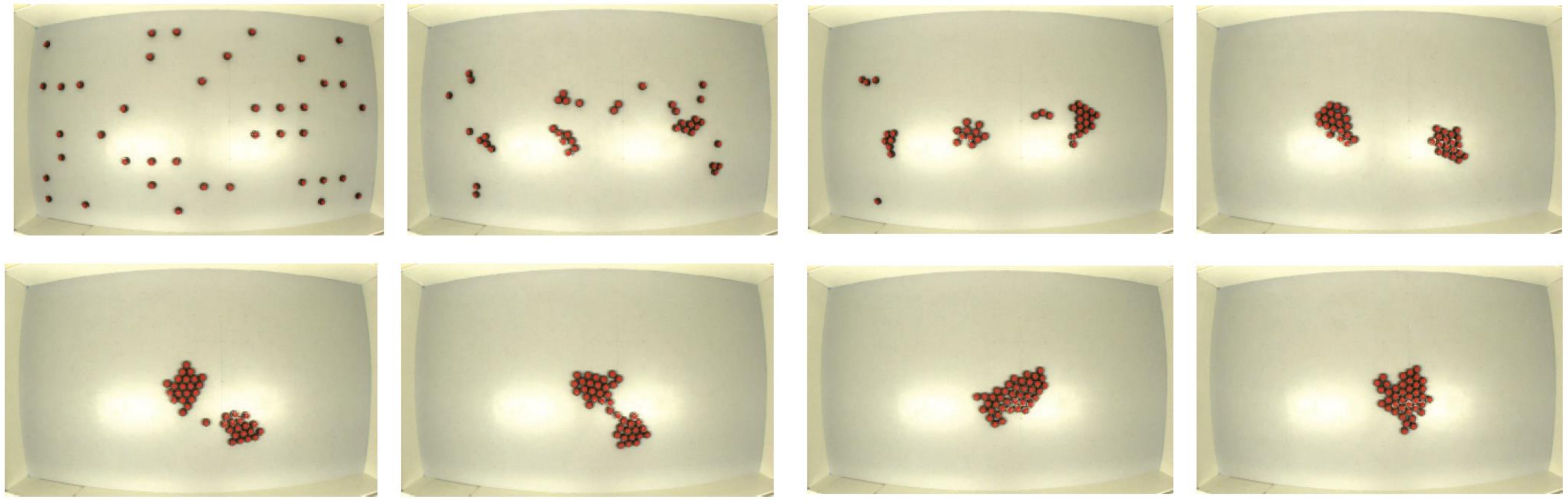
The Gauci et al. Algorithm

Theorem. One robot using controller $\boldsymbol{x}^*$ will always aggregate with another static robot or static circular cluster.

Theorem. Two robots both using controller $\boldsymbol{x}^*$ will always aggregate.

- Time bounds are proven for both cases.

Experimental and simulation results suggested that $n > 2$ robots using controller $\boldsymbol{x}^*$ would always aggregate, but this <u>was not proven</u>.



Summary of Results

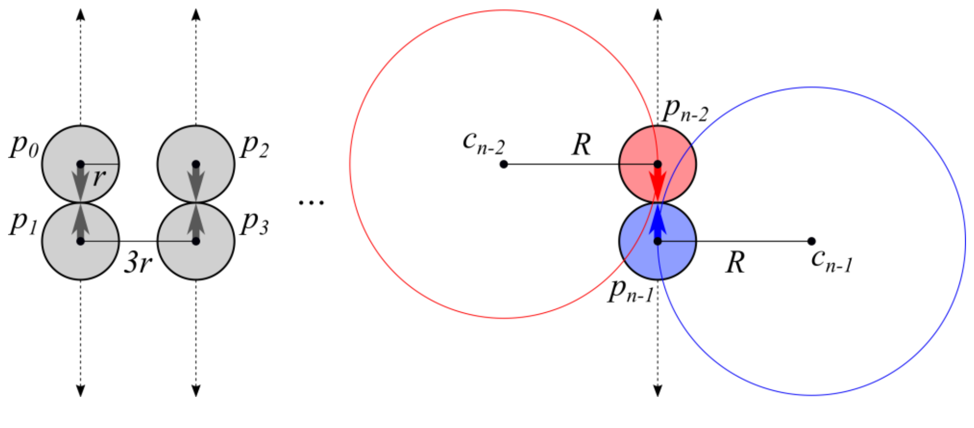
Conjecture. A system of $n > 2$ robots each using $\boldsymbol{x}^*$ will always aggregate.

Our Contributions

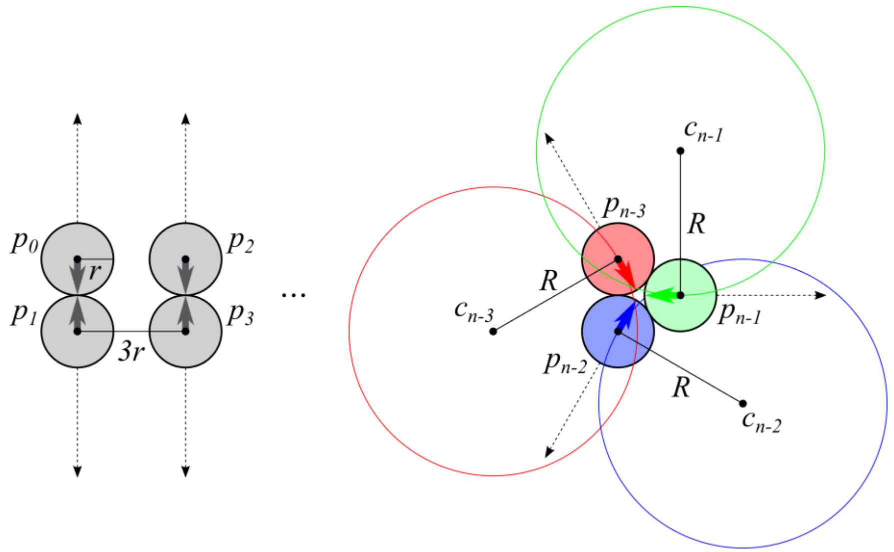
- We prove this conjecture does not hold in general, identifying deadlocked configurations.
- We demonstrate the algorithm is robust to error/noise in its sensors and movements.
- We prove a linear aggregation time for systems of $n = 2$ robots with cones-of-sight (a linear speedup over those with lines-of-sight) and demonstrate faster aggregation in larger systems with small cones-of-sight in simulation.

Impossibility of Aggregation for $n > 3$ Robots

Theorem. For all $n > 3$ and all clockwise-searching controllers $\boldsymbol{x}$ (including $\boldsymbol{x}^*$), there exists an initial configuration of n robots from which the system will not aggregate using controller $\boldsymbol{x}$.



$n > 3$ even

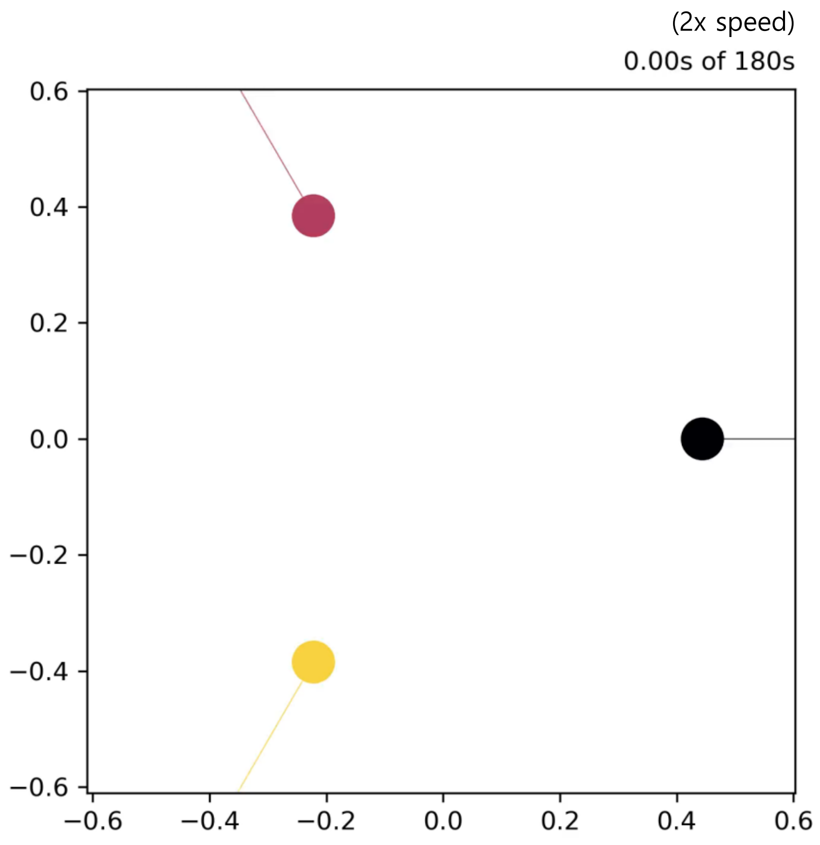


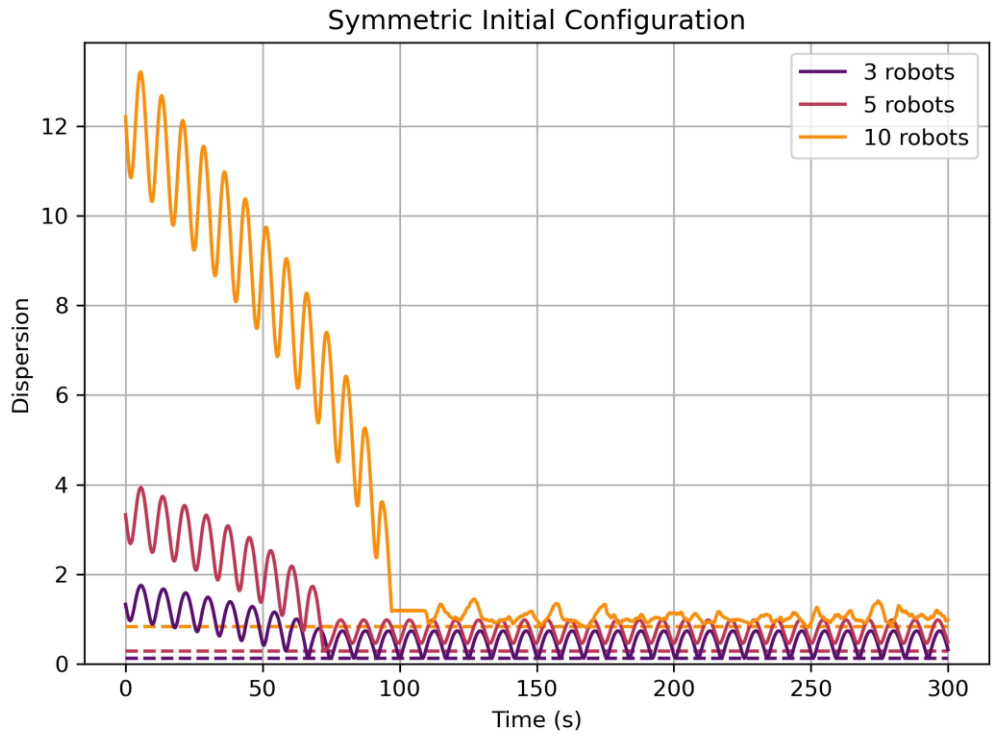
$n > 3$ odd

Symmetric Configurations

At Dagstuhl Seminar 18331, Aaron Becker conjectured that symmetric configurations would cause “livelock” where robots would be trapped in symmetric traversals indefinitely.

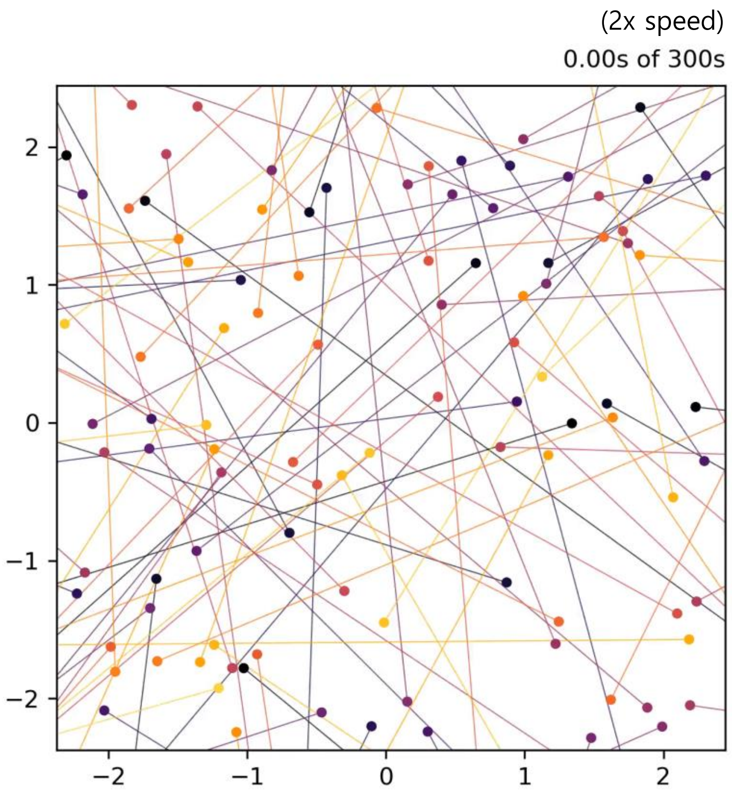
We disprove this result via simulation:

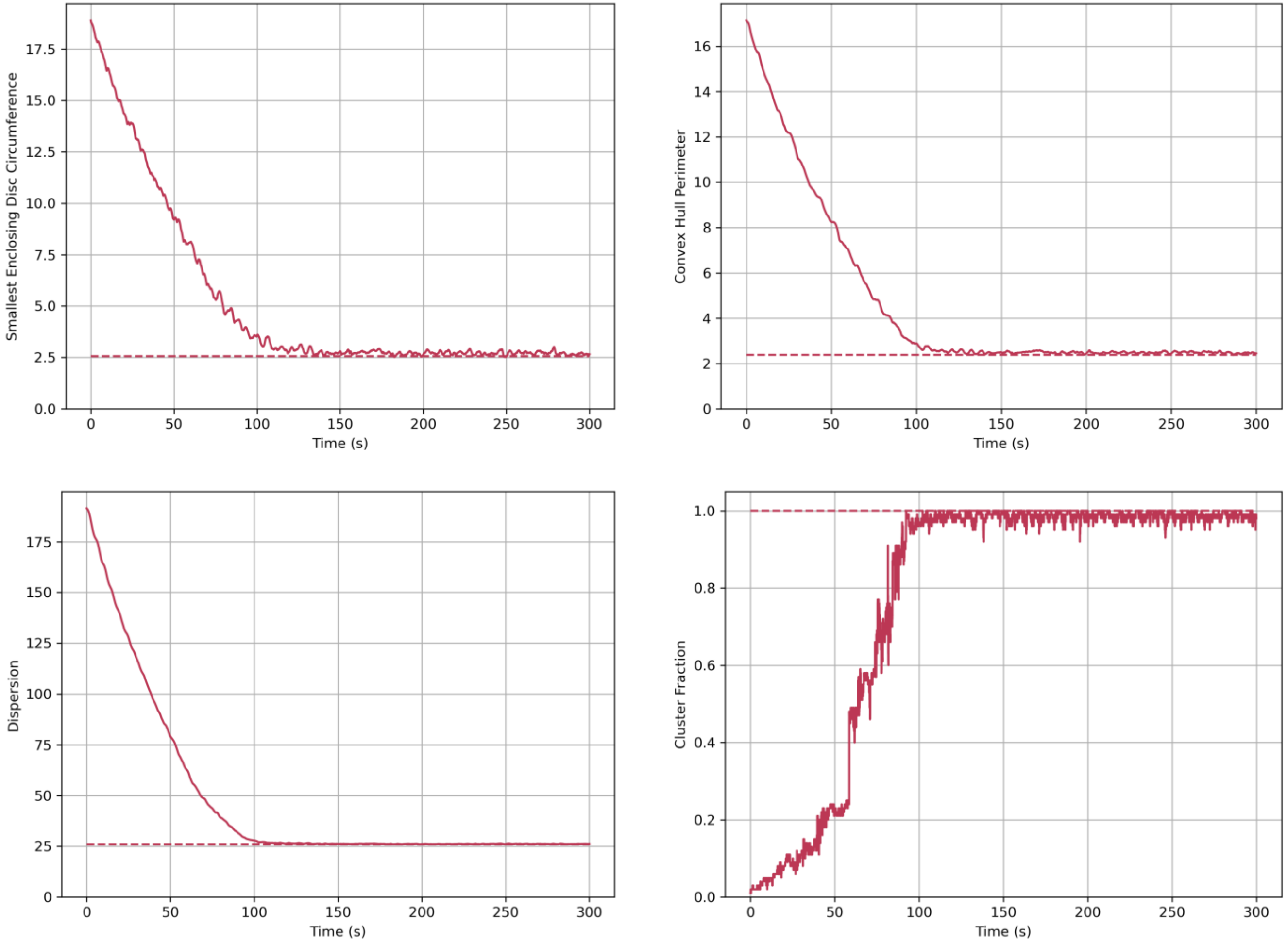




Baseline Behavior

Simulation video and aggregation metrics for a 300s run of a system with $n = 100$ robots.





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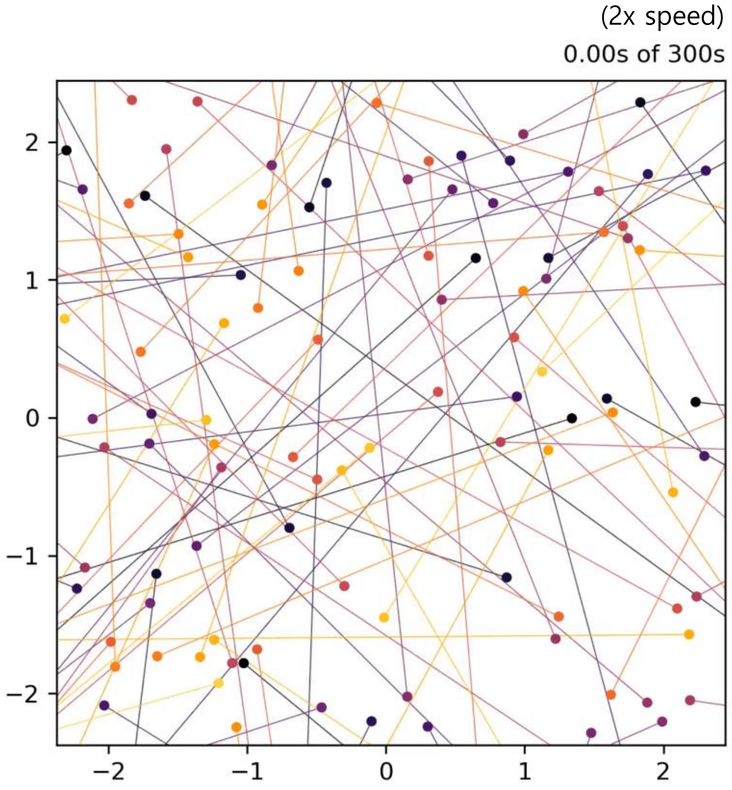
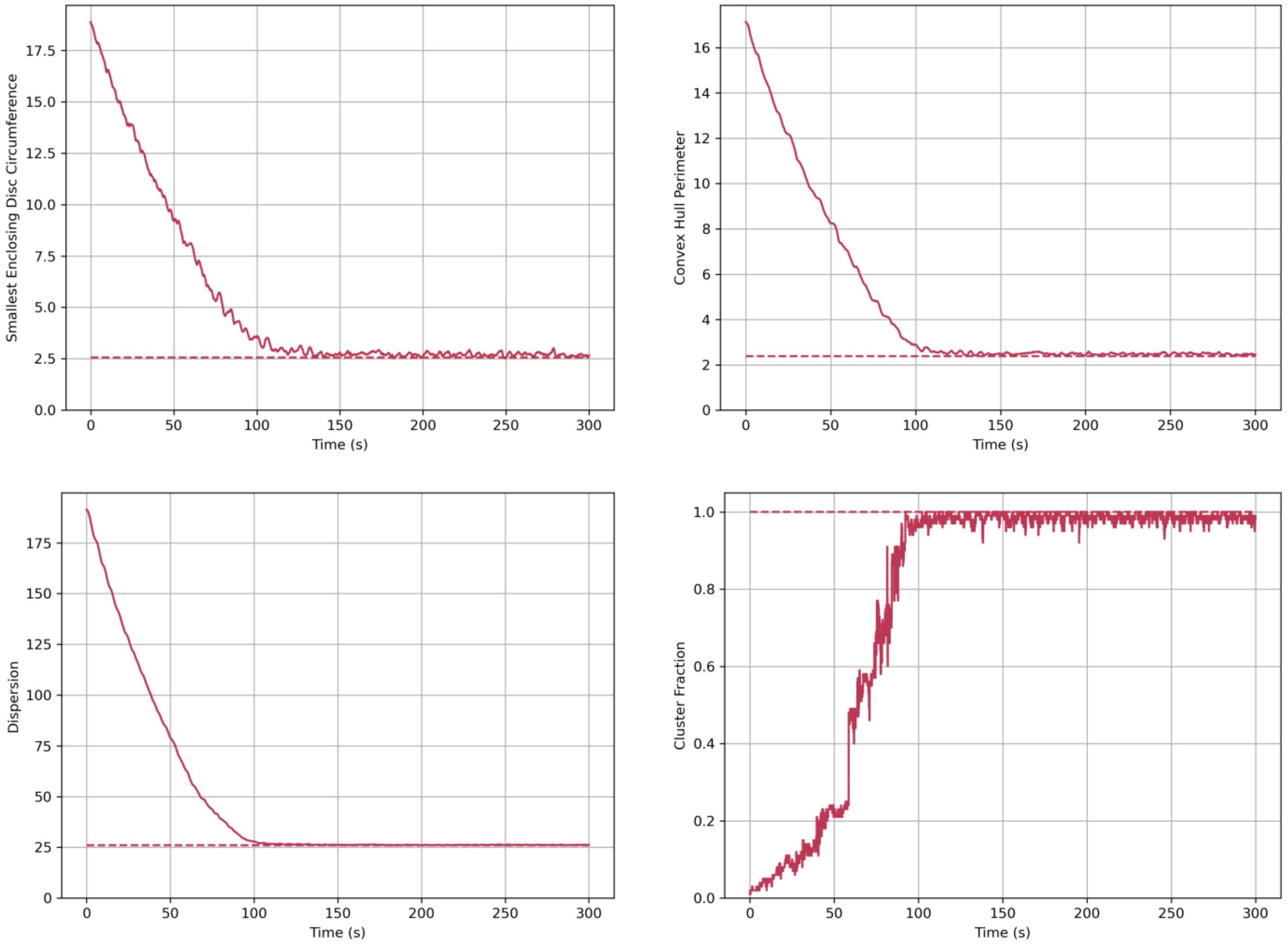
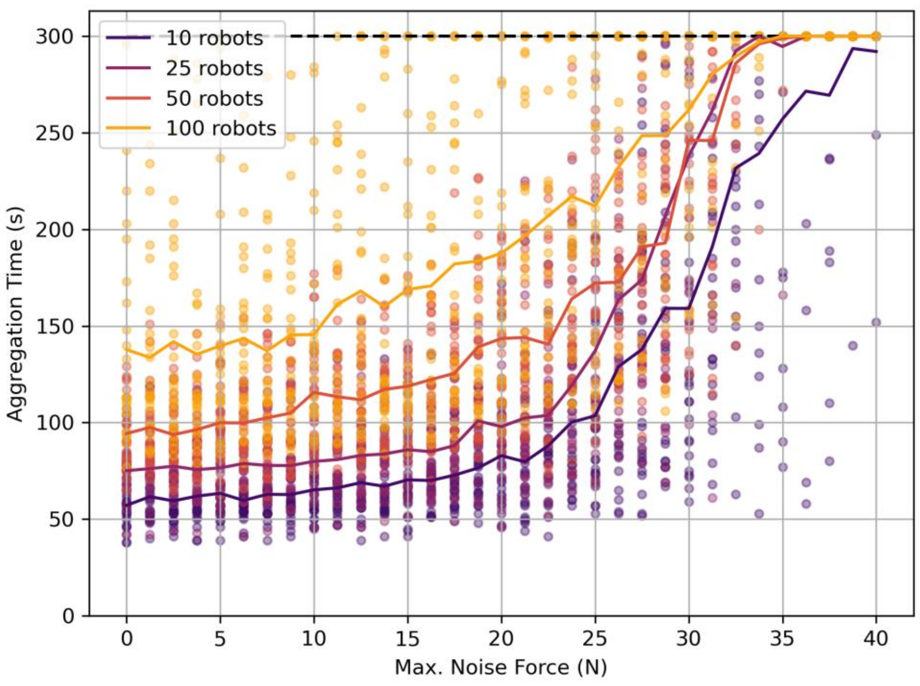


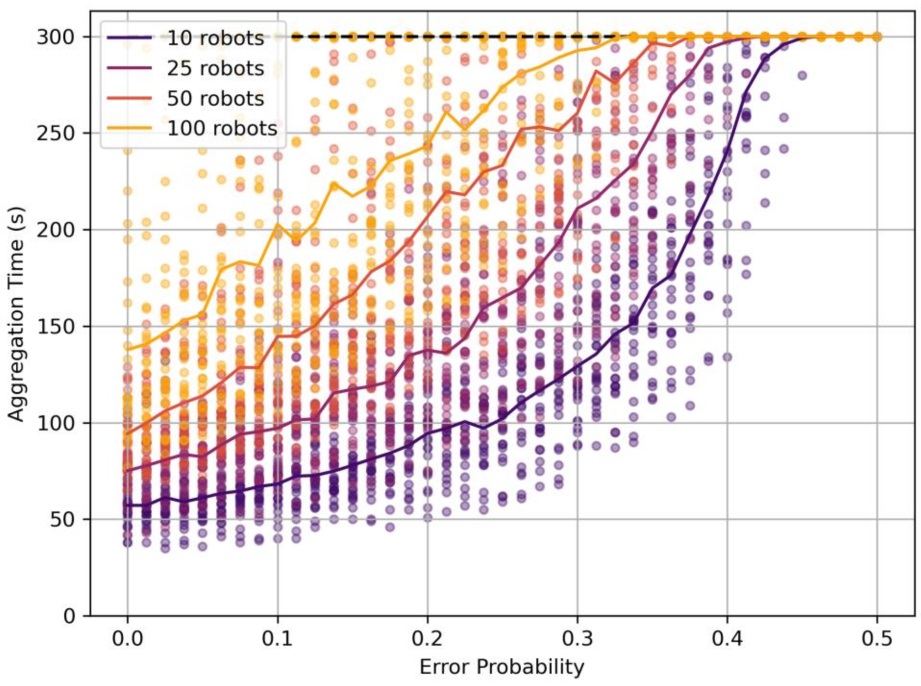


Robustness to Error and Noise

Motion Noise. Each robot at each time step experiences an applied force of a random magnitude in $[0, m^*]$ (N) in a random direction.

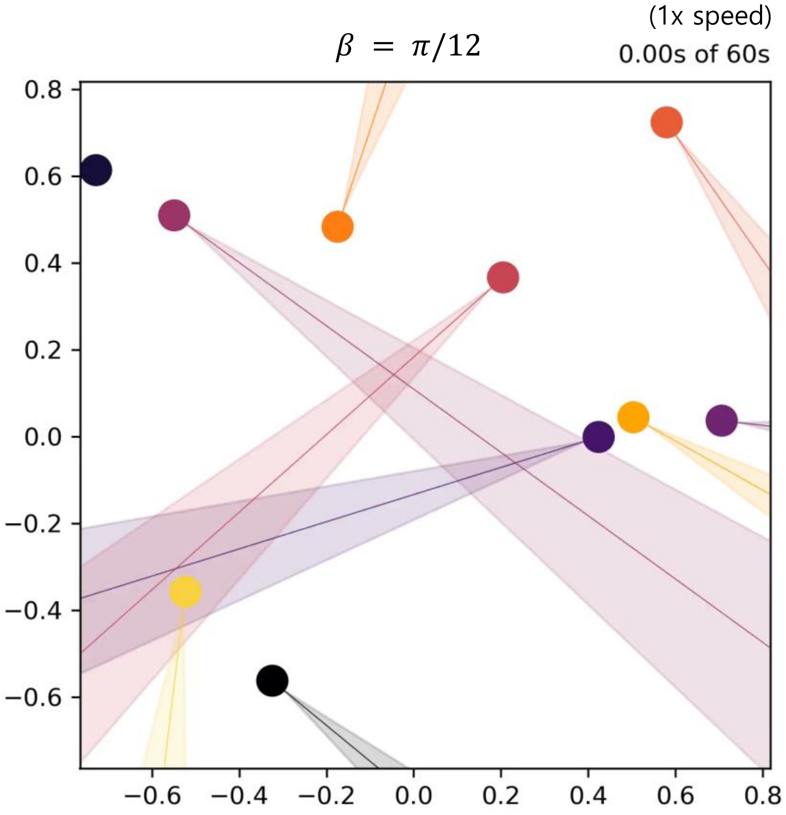
Error Probability. Each robot has the same probability $p \in [0,1]$ of receiving the incorrect feedback from its sight sensor at each time step. (Note: this is the same as Gauci et al.'s "sensory noise" when false positive and false negative probabilities are both p).

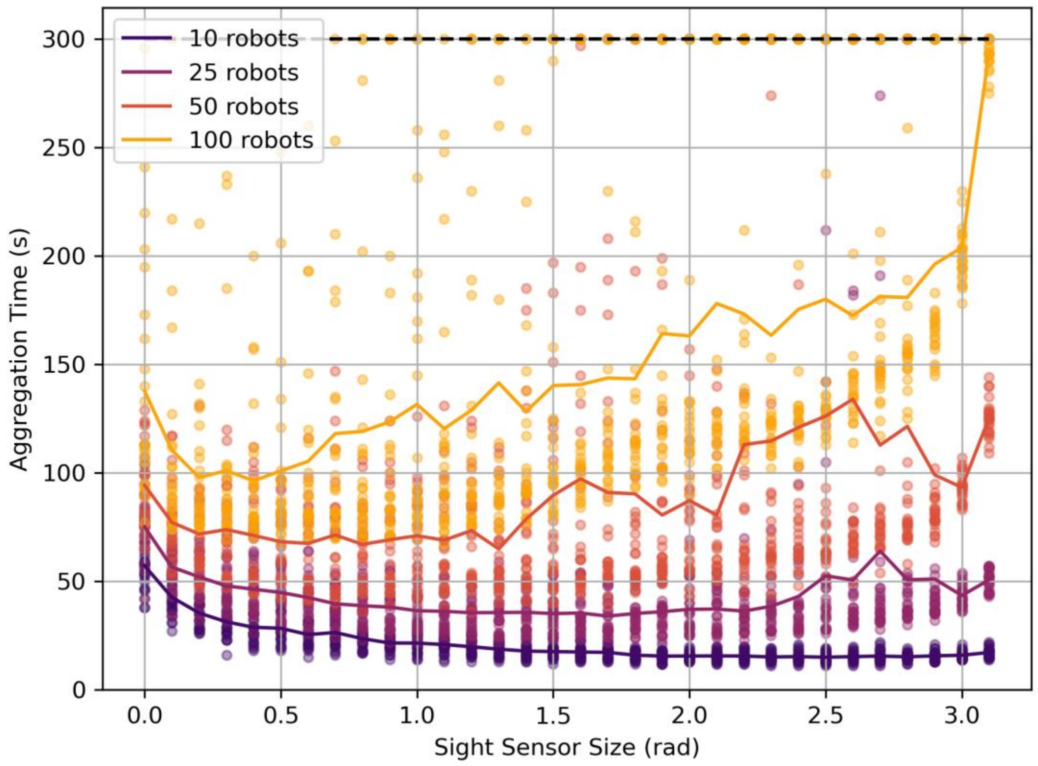




Using a Cone of Sight Sensor

As sensor size increases, the span of the sensor's information increases, but the local specificity of that information decreases. How does sensor size impact the algorithm’s efficiency?





Using a Cone of Sight Sensor

Theorem. One moving robot using $\boldsymbol{x}^*$ with a cone-of-sight sensor of size $\beta \in (0, \pi)$ will always aggregate with another static robot in

$$m < \left\lceil \frac{(d_0 - R - r_i - r_j)(R + 2R_i)}{2\sqrt{3}Rr_i \sin\left(\left(1 - 1/\sqrt{3}\right) \cdot \beta/2\right)} \right\rceil$$

rotations around its center of rotation, where d_0 is the initial distance between the robots.

This demonstrates a linear speedup with cone-of-sight sensors for $n = 2$ robots.

Line-of-sight (Gauci et al.)	**Cone-of-sight (This Paper)**
$m \in \mathcal{O}(d_0^2)$	$m \in \mathcal{O}(d_0)$

Thank you!

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