Human-Swarm Interaction

a brief primer

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Swarm Properties

- simple and distributed - from the operator's perspective
- distributed algorithms and information processing
- emergence of global behaviors from local interactions.

Robots in other multi-robot systems:

- have explicitly represented goals,
- form and execute both individual and group plans,
- have advanced capabilities and can assume different roles.

Conjecture: Large-scale systems look like swarms.

Swarm Algorithms

1) Bio-inspired
- wide range of behaviors
- testbed & systems

2) Control Theory
- strong theory
- simplified assumptions

3) Amorphous Computing
- distributed computation
- programming language

4) Physics-inspired
- inspiration from physics
- passive interactions

Role of Operators

1. Recognize and mitigate shortcomings of the autonomy
2. Contribute information not accessible to the autonomy
3. Convey changes in intent as mission goals change
4. Debug

Early Questions

(a) How do the properties of the communication channel between operator and swarm affect human-swarm interactions, such as the ability to observe and control the swarm?

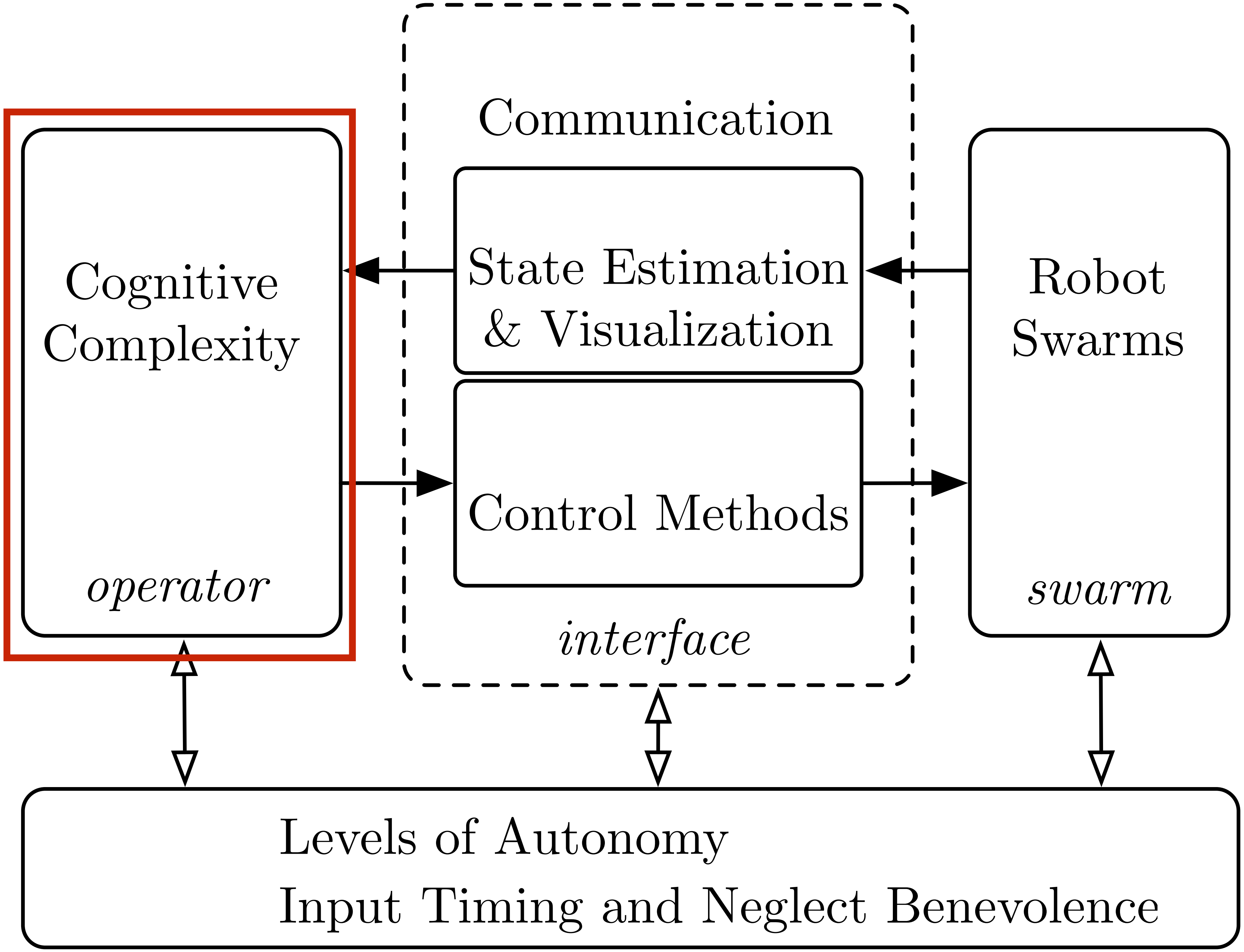
(b) How can an operator observe a swarm and its dynamics?

(c) What are the different control methods used, and how do they affect the ability of an operator to control a swarm?

(d) What is the relevance of the notion of levels of automation in HSI and how has it been exploited and studied?

(e) How do swarm dynamics affect the ability of the operator to control the swarm?

Kolling, A.; Walker, P.; Chakraborty, N.; Sycara, K.; Lewis, M., "Human Interaction With Robot Swarms: A Survey," *in Human-Machine Systems, IEEE Transactions on , vol.PP, no.99, pp.1-18*, 2015



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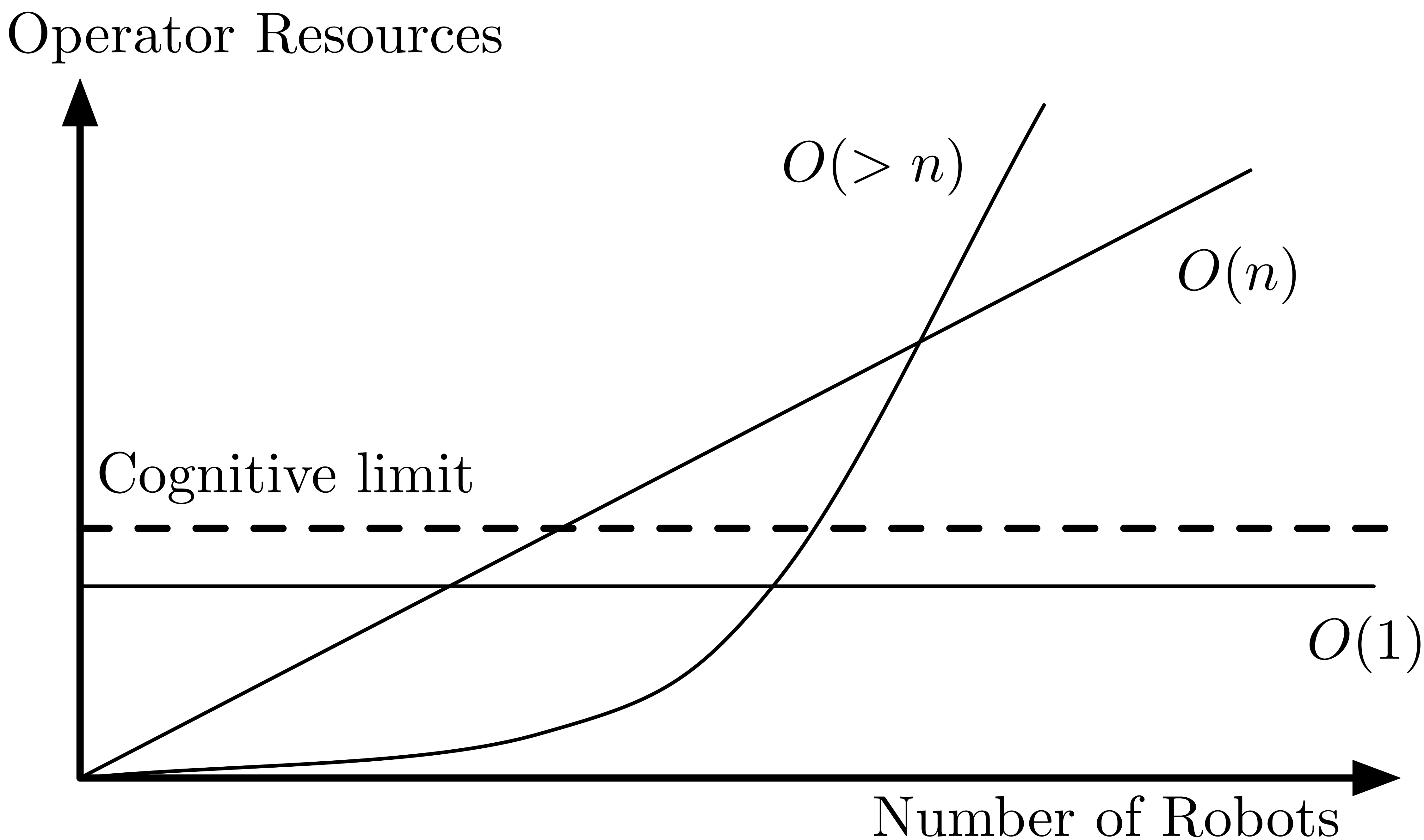
Cognitive Complexity

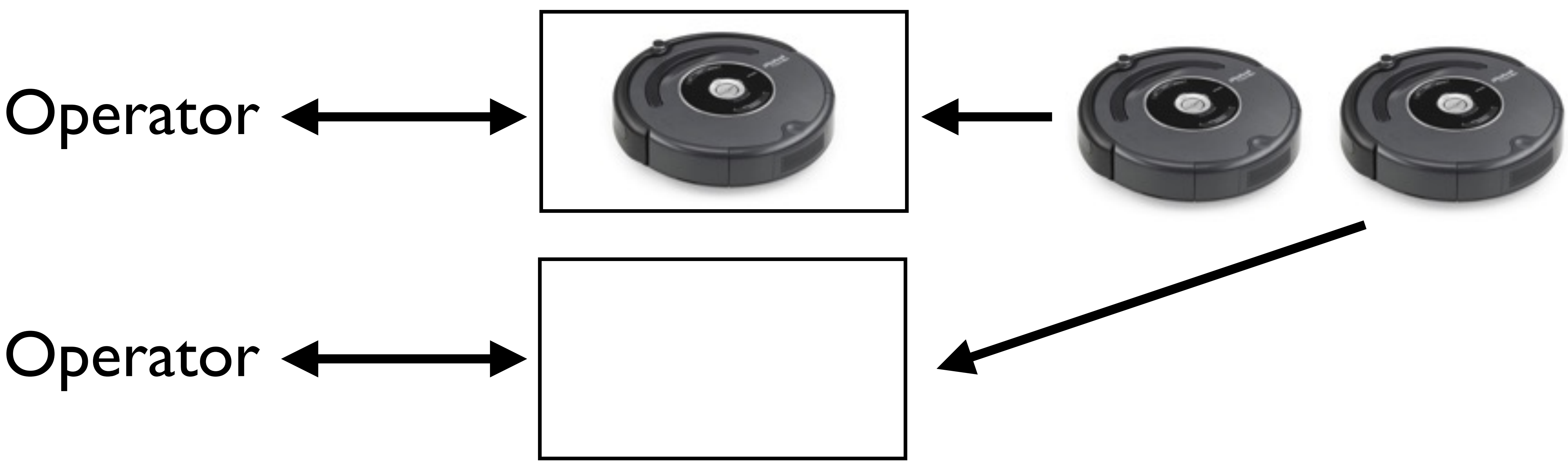


M. Lewis, "Human interaction with multiple remote robots," *Reviews of Human Factors and Ergonomics*, vol. 9, no. 1, pp. 131–174, 2013.

Neglect Tolerance

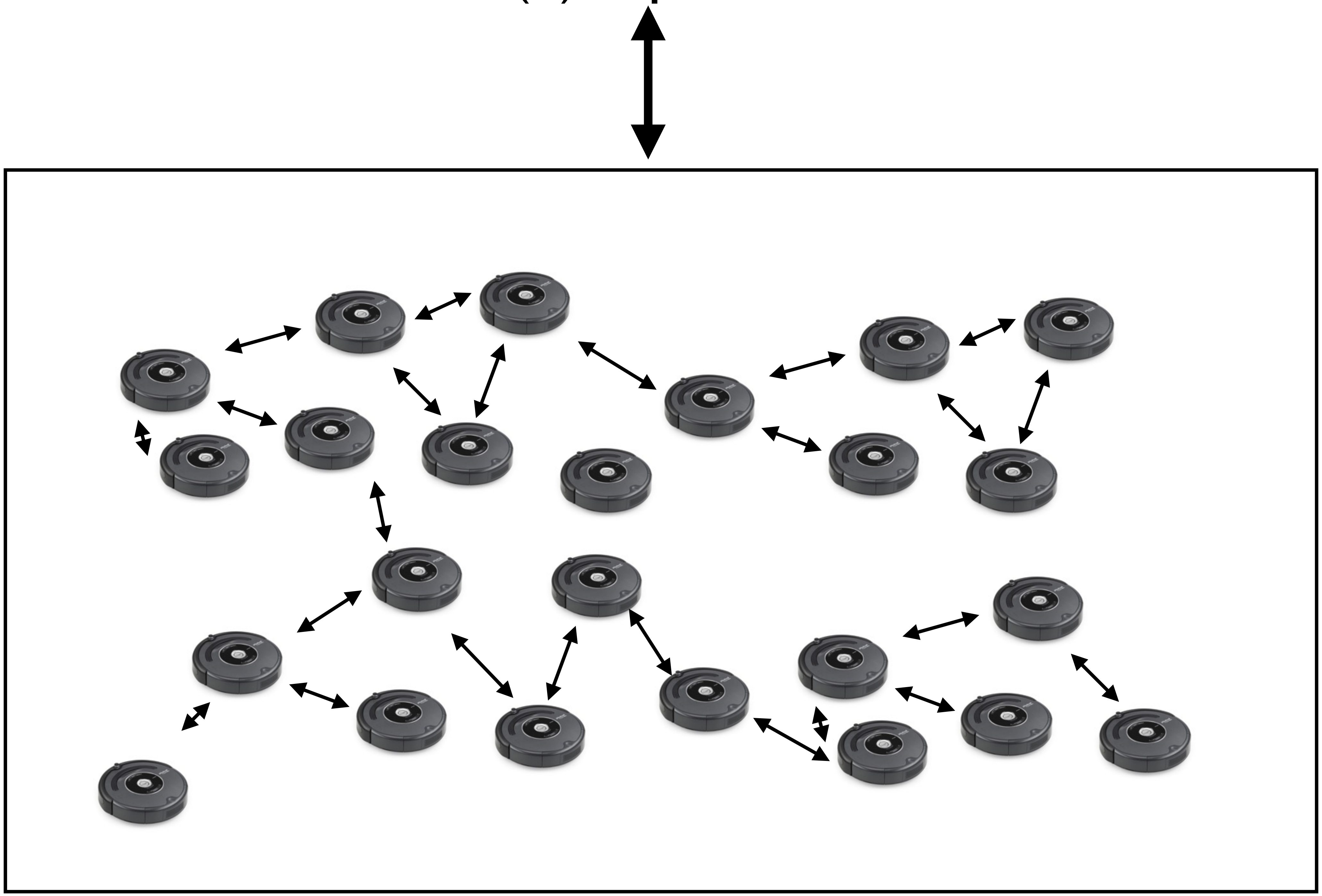
- schedule operator attention
- autonomy manages interdependencies
- focus on studying operator behavior for local tasks

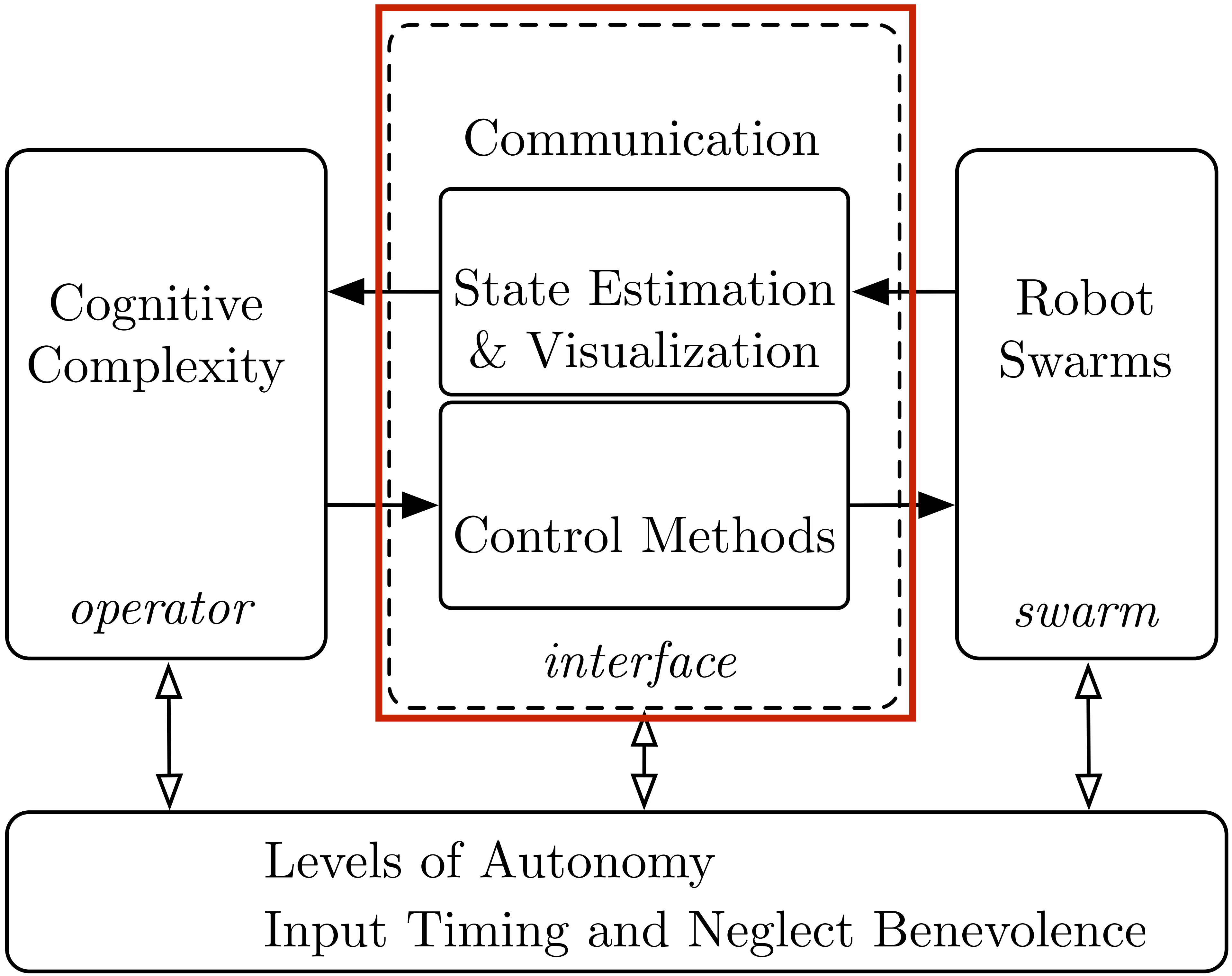
O(n) Multi-Robot Call Center



Chien, S., Mehrotra, S., Brooks, N., Lewis, M. & Sycara, K. Scheduling operator attention for multi-robot control, IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS'12), October 7-12, Villamoura, Portugal, 2012

O(1) Operator





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Communication

Remote Interaction

- remote or dangerous environments
- depends on infrastructure
- introduces a central element
- Challenge: changes in network topology: connectivity/fragmentation, bandwidth[1], latency[2]

draw from research in mobile networks

Proximal Interaction

- shared environment
- less infrastructure
- naturally distributed
- Challenge: lack of control/access

draw from methods for gesture, speech and face engagement and specialized devices

[1] S. Nunnally, P. Walker, A. Kolling, N. Chakraborty, M. Lewis, K. Sycara, and M. Goodrich, "Human influence of robotic swarms with bandwidth and localization issues," in *Systems, Man, and Cybernetics (SMC), 2012 IEEE International Conference on*. IEEE, 2012, pp. 333–338.

[2] P. Walker, S. Nunnally, M. Lewis, A. Kolling, N. Chakraborty, and K. Sycara, "Neglect benevolence in human control of swarms in the presence of latency," in *Systems, Man, and Cybernetics (SMC), 2012 IEEE International Conference on*. IEEE, 2012, pp. 3009–3014.

State Estimation & Visualization

- visualize the swarm state
- facilitate the understanding of swarm dynamics
- deal with incomplete information (errors, latencies, etc.)
- develop predictive displays

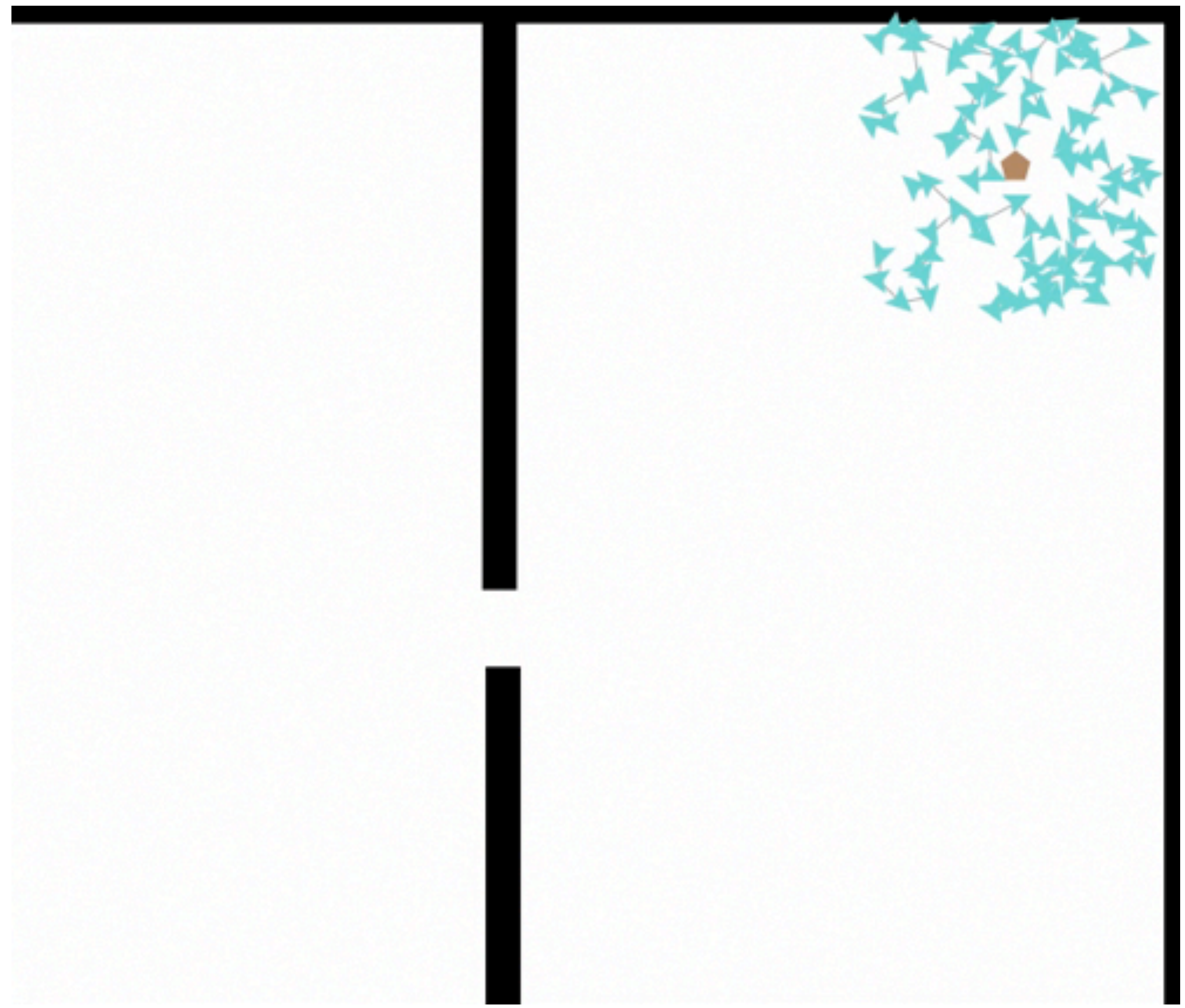
Challenge: how can operators understand and predict the impact of controls on swarm dynamics?

Opportunity: contribute to basic research in cognition and neuroscience with cognitive models for perception

B. Tabibian, M. Lewis, C. Lebiere, N. Chakraborty, K. Sycara, S. Ben- nati, and M. Oishi, "Towards a cognitively-based analytic model of human control of swarms," in *2014 AAAI Spring Symposium Series*, 2014.

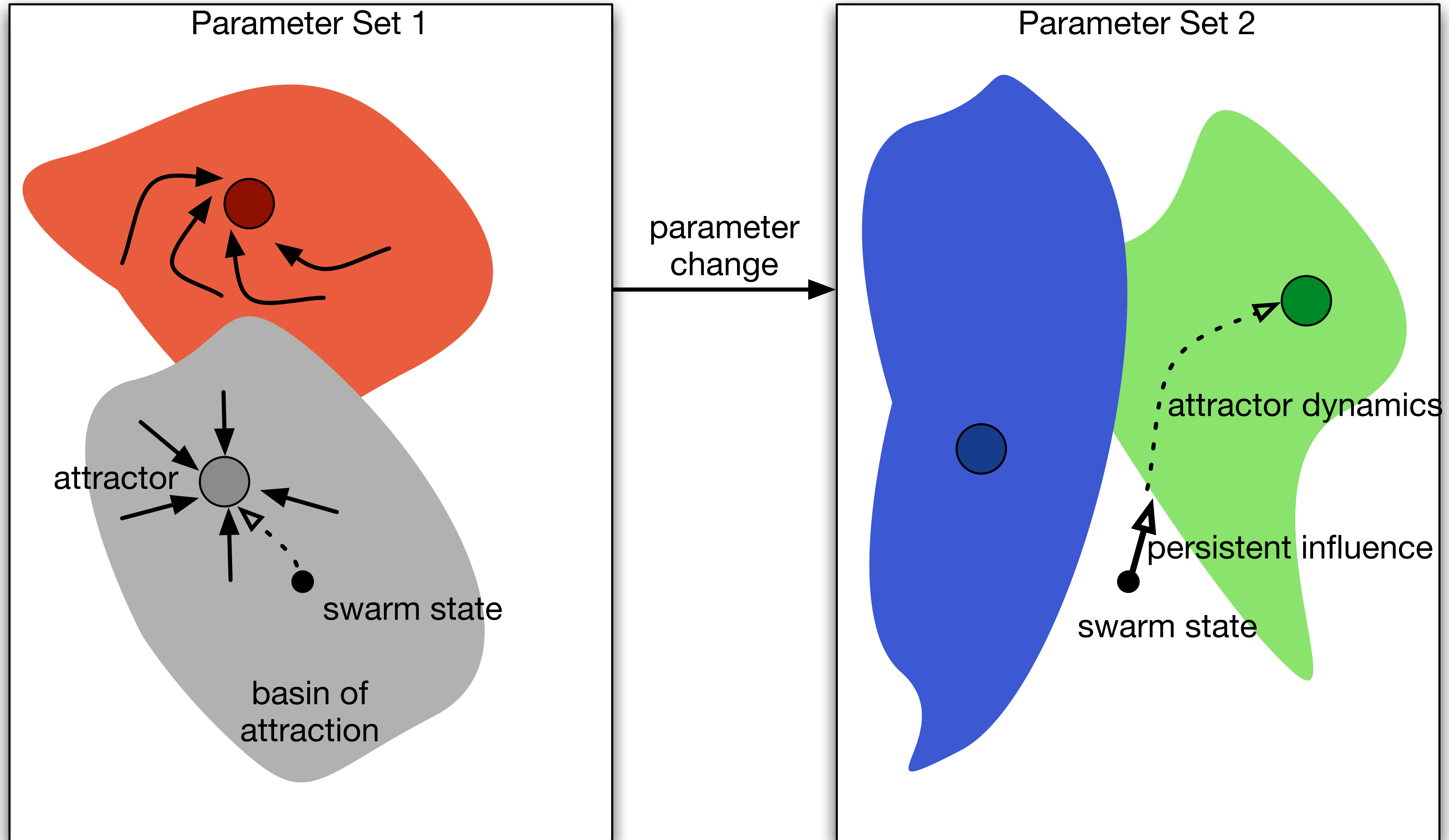
S. Nagavalli, N. Chakraborty, and K. Sycara, "A study on the bounds of neglect benevolence in input timing for human interaction with robotic swarms," in *Human-Robot Interaction (HRI), 2015 ACM/IEEE International Conference on*, 2015.

Control Types



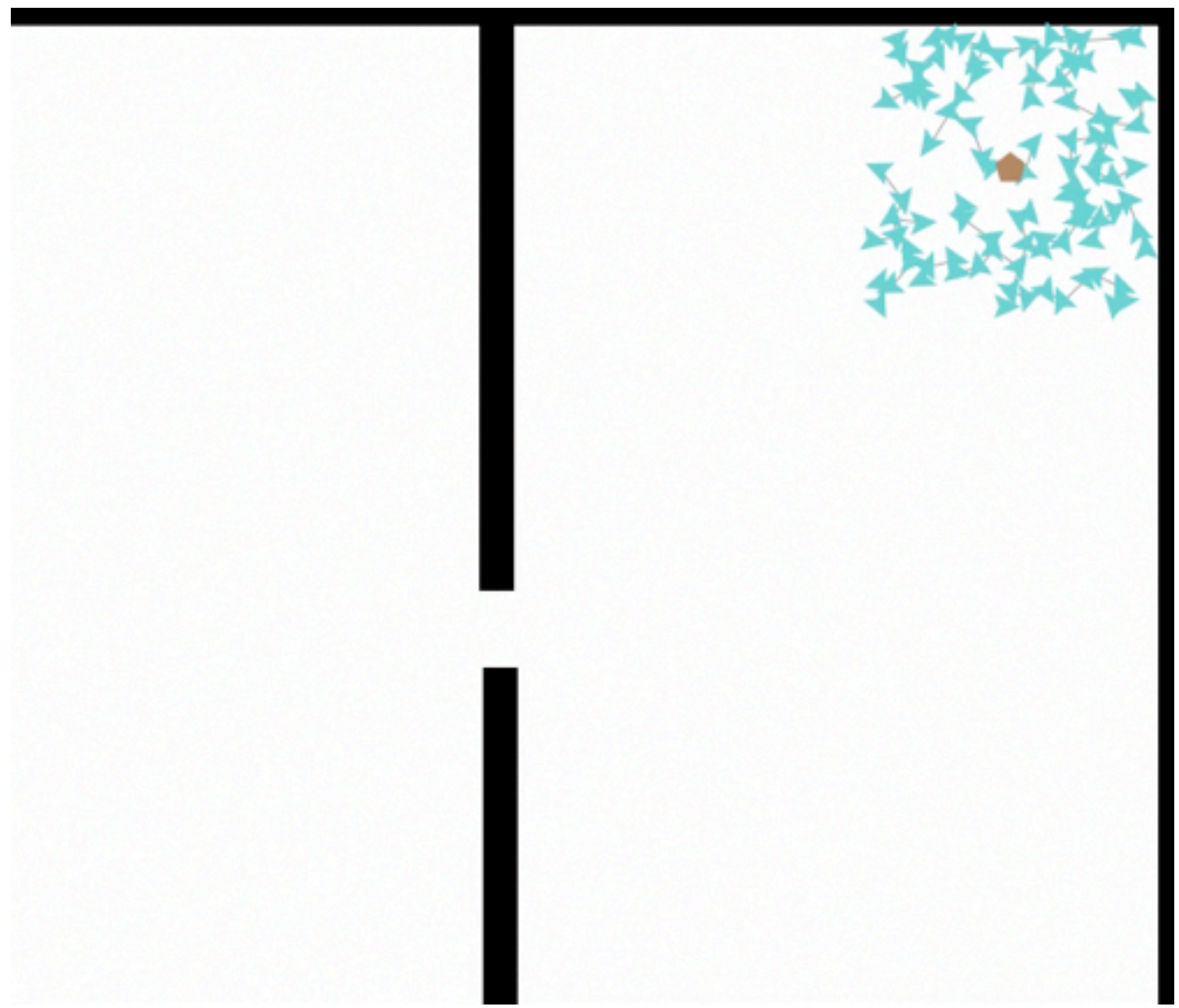
1) switching between algorithms/behaviors

- appears easier to learn; benefits from behavior libraries
- challenges: right behavior, timing, and state estimation

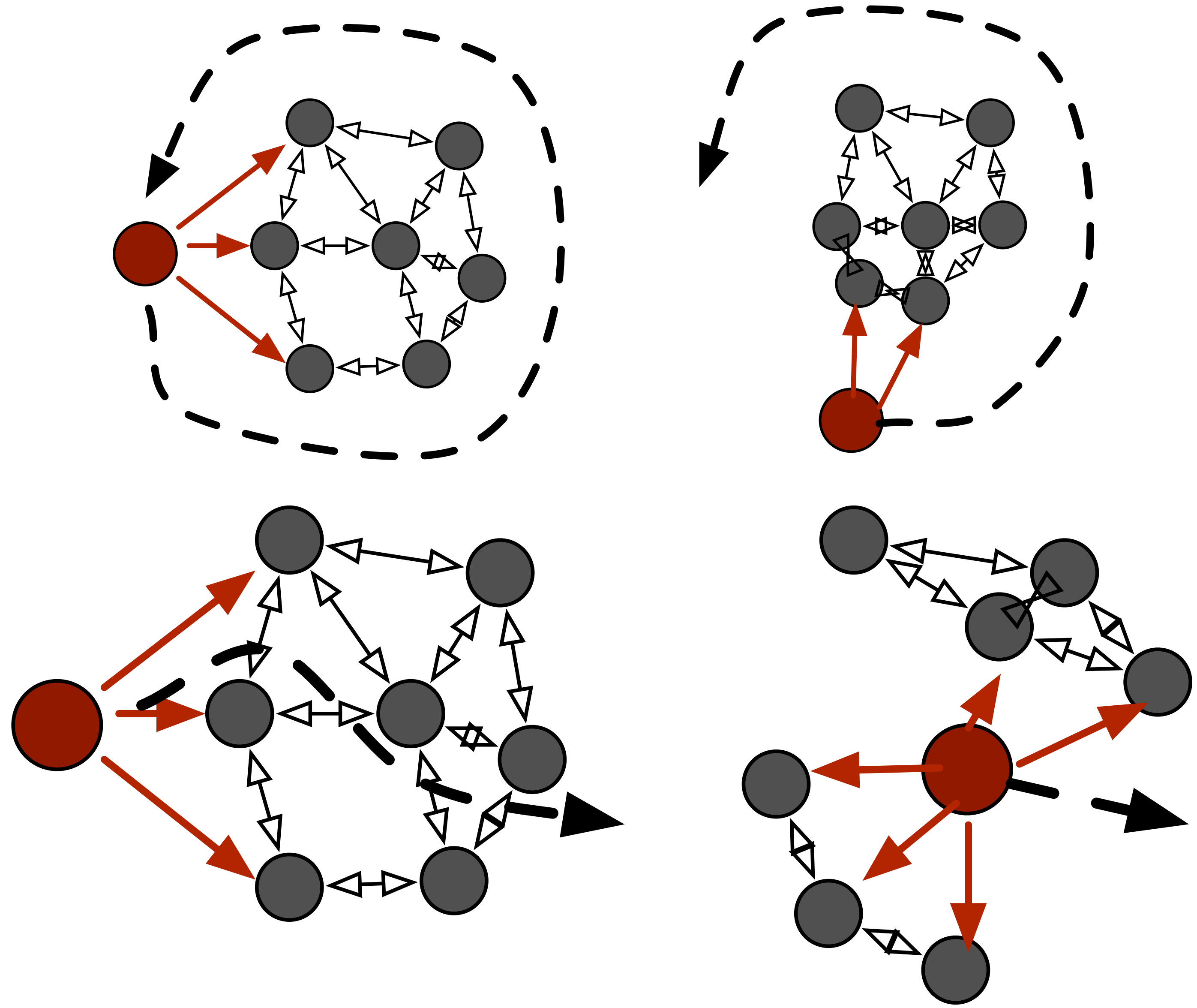


2) changing parameters of a control algorithm

- indirect effects; wide range of changes
- challenges: requires tools to help with settings; predictability



3) indirect control via environmental influences
   - location-dependent; persistent; real or virtual
   - virtual pheromones, virtual beacons, and amorphous computing
   - hard to learn for operators



4) control through selected swarm members/leaders.

- more engaging forms of control, e.g. teleoperation
- influence propagates through the leader to the swarm
- methods available for discrete and continuous control inputs
- tacit vs explicit influence

relevance for multi-robot systems when an operator controls a single robot
and disturbs the autonomous coordination of the rest of the system

Amirpour S., Walker, P., Lewis, M., Chakraborty, N., Sycara, K. Explicit vs Tacit Leadership in Influencing the Behavior of Swarms, International Conference on Robotics and Automation (ICRA), Hong Kong, China, May 31-June 7, 2014.

Swarm Concepts

Neglect Benevolence

Observation: a swarm system stabilizes over time and an operator input can disturb this process

What kinds of systems exhibit neglect benevolence?

1) Most swarm systems (rendezvous, deployment, foraging …)
2) Stable LTI systems [2][3]
3) …

[1] P. Walker, S. Nunnally, M. Lewis, A. Kolling, N. Chakraborty, and K. Sycara, "Neglect benevolence in human control of swarms in the presence of latency," in *Systems, Man, and Cybernetics (SMC), 2012 IEEE International Conference on*. IEEE, 2012, pp. 3009–3014.
[2] Nagavalli, S., Luo, L., Chakraborty, N., Sycara, K., "Neglect Benevolence in Human Control of Robotic Swarms", *International Conference on Robotics and Automation (ICRA),* Hong Kong, China, May 31-June 7, 2014
[3] Nagavalli, S., Chien, S.Y, Lewis, M. Chakraborty, N., Sycara, K, "Bounds of Neglect Benevolence in Input Timing for Human Interaction with Robotic Swarms", *International Conference on Human-Robot Interaction*, Portland, Ore., March 2-5, 2015

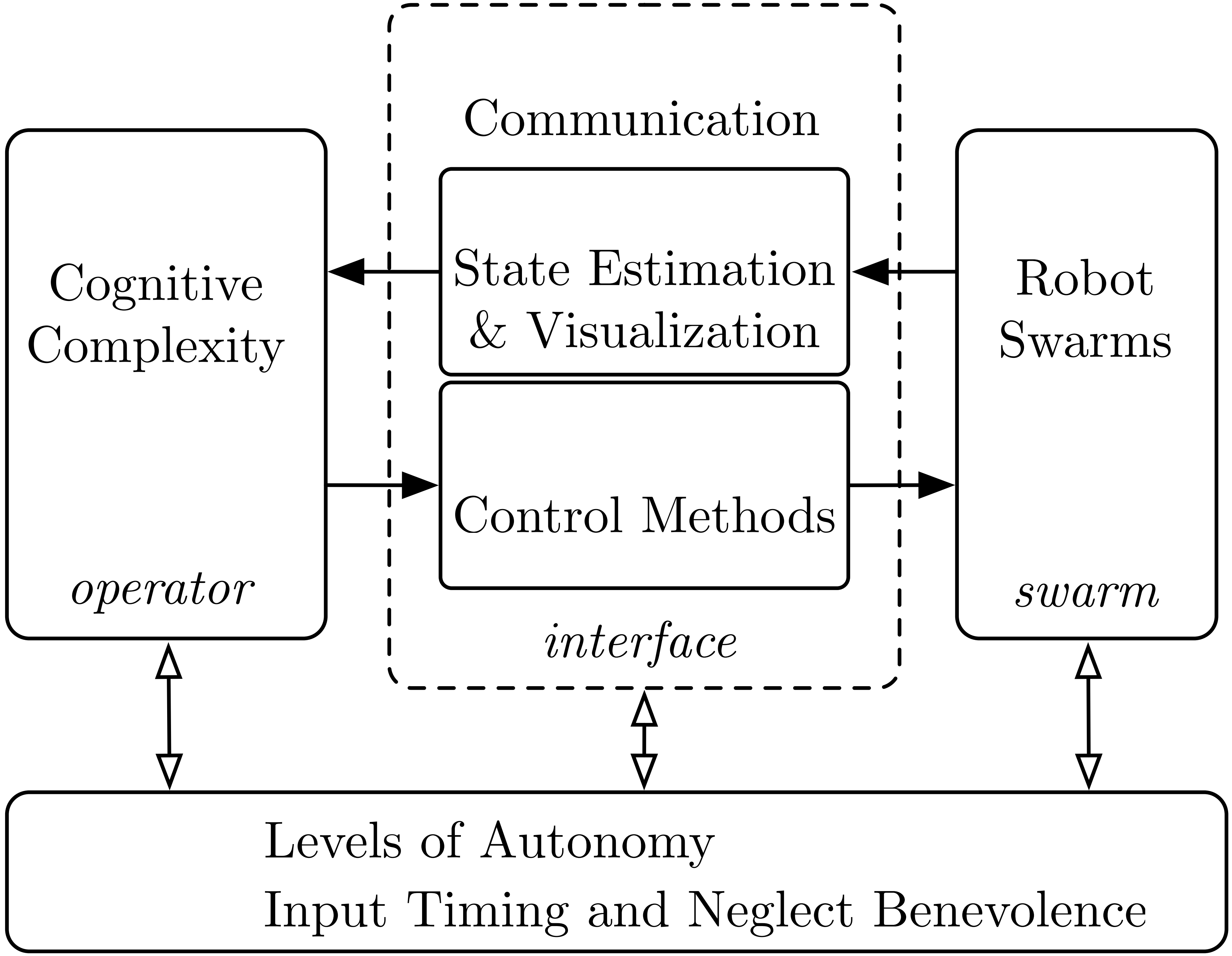
Levels of Autonomy

- autonomy spectrum for HSI [1]
- switchable levels of autonomy [2]
- autonomy can increase situation awareness

Need more specific and refined models of autonomy levels

[1] G. Coppin and F. Legras, "Autonomy spectrum and performance perception issues in swarm supervisory control," *Proceedings of the IEEE*, vol. 100, no. 3, pp. 590–603, 2012.

[2] P. Walker, S. Nunnally, M. Lewis, N. Chakraborty, and K. Sycara, "Levels of automation for human influence of robot swarms," in *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, vol. 57, no. 1. SAGE Publications, 2013, pp. 429–433.


Communication
State Estimation & Visualization
Control Methods
interface
Cognitive Complexity
operator
Robot Swarms
swarm
Levels of Autonomy
Input Timing and Neglect Benevolence

Selection and Sub-Swarms

- most control types involve the implicit or explicit selection of robots and subswarms
- most studies allow operators to select or split swarms

O(1) control with k subswarms turns into O(k) with each subswarm acting like a robot in a multi-robot system

Future Work

1) Suitability of Control Type Relative to Task and Environment:
   - suitability: tasks, environments, communication and timing
   - compare effectiveness, scope, impact, training requirements

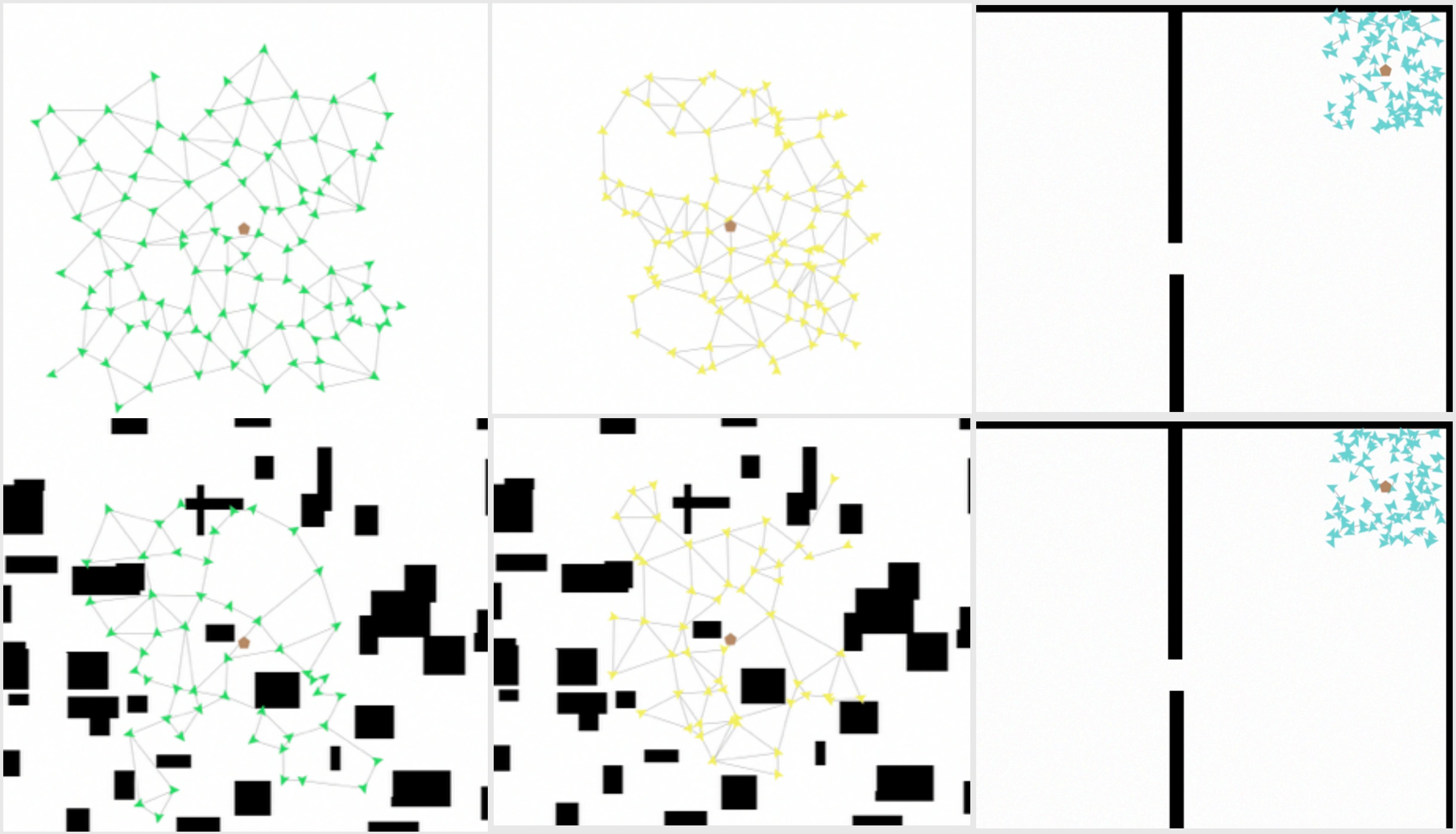
2) Swarm Visualization and Understanding of Dynamics:
   - what patterns can be identified and classified by humans?
   - context switching

3) Input timing and Neglect Benevolence:
   - formal and experimental perspective
   - when is it learnable and controllable?

4) Swarm Metrics and Experiments:
   - beyond convergence proofs
   - performance and temporal characteristics

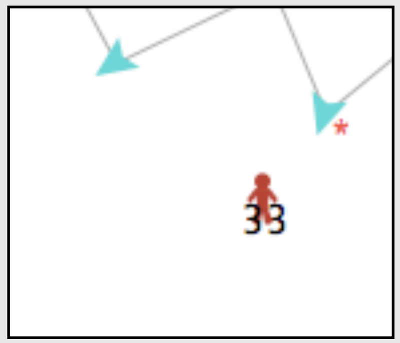
Comparison of Two Control Types

A. Kolling, K. Sycara, S. Nunnally, and M. Lewis, "Human swarm interaction: An experimental study of two types of interaction with foraging swarms," *Journal of Human-Robot Interaction*, vol. 2, no. 2, pp. 103–128, 2013.



stop come rendezvous deploy random heading leave

Information Foraging



collect information, relayed via communication network, from targets spawning at random throughout the map

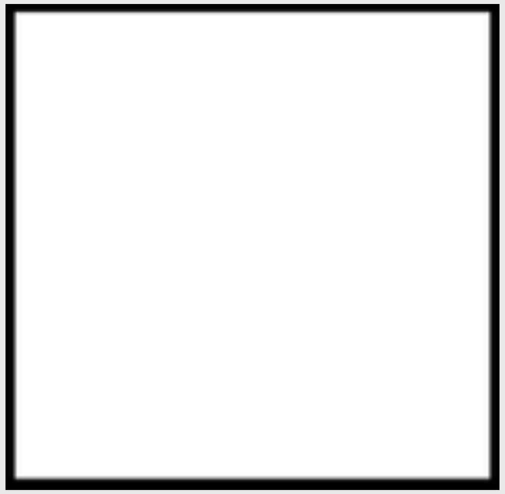
improve coverage

maintain network

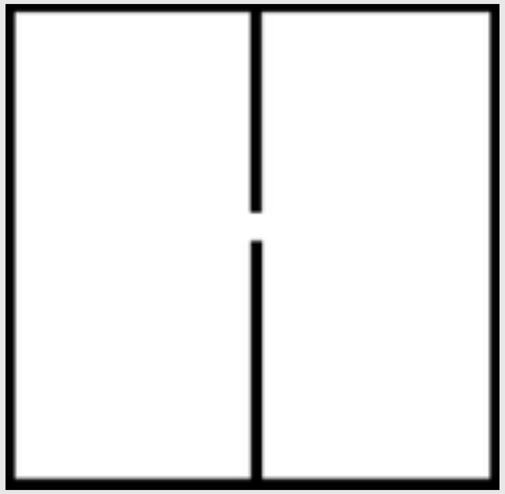
adapt to changes

adapt to the map

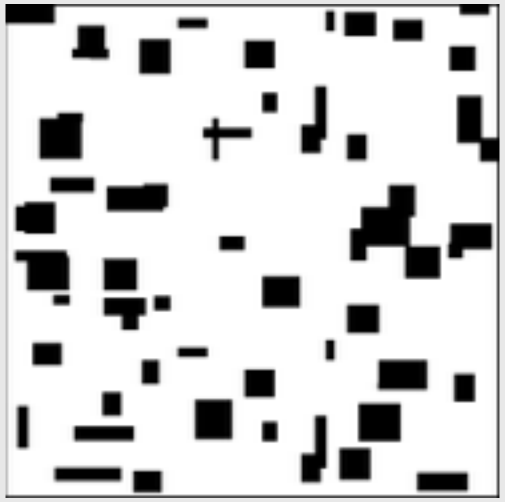
Open



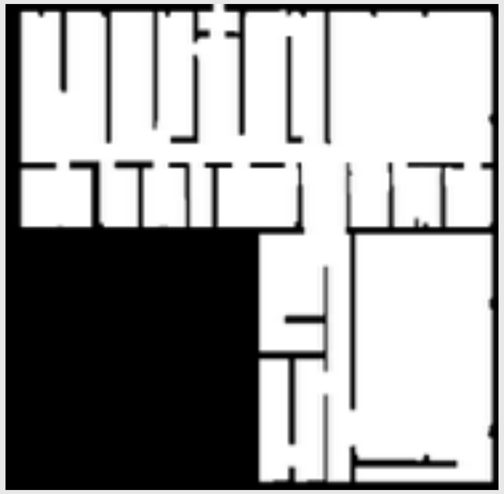
Two-room



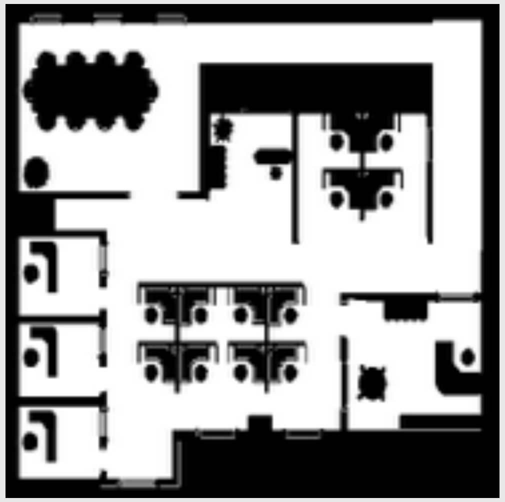
Cluttered



Structured



Structured Cluttered



Questions

- How do selection, beacon and autonomous control **perform**?
- What is the impact of **complex maps**?
- How do participants make use of the available **behaviors**?
- How do the control methods **scale** to larger swarms?

Results

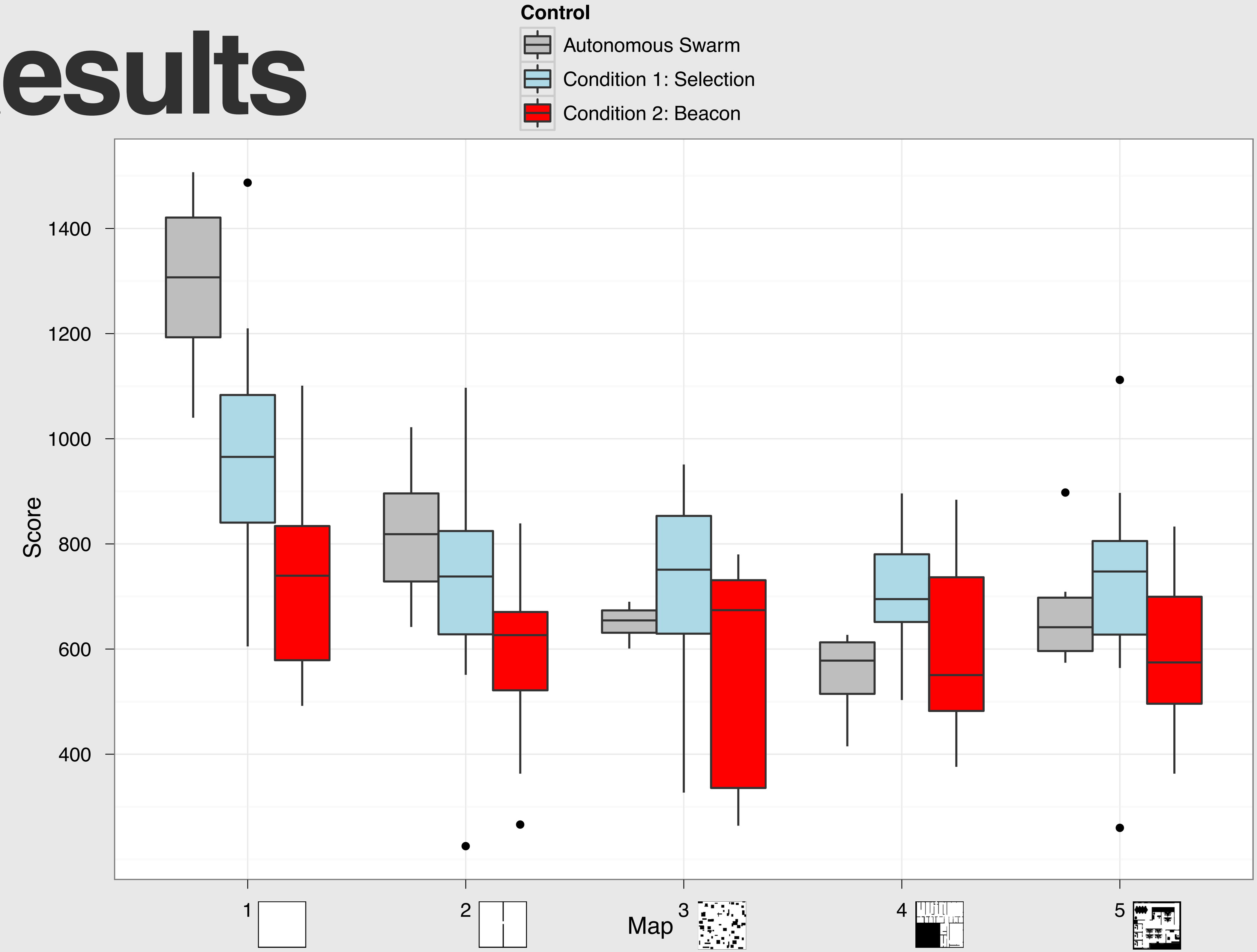
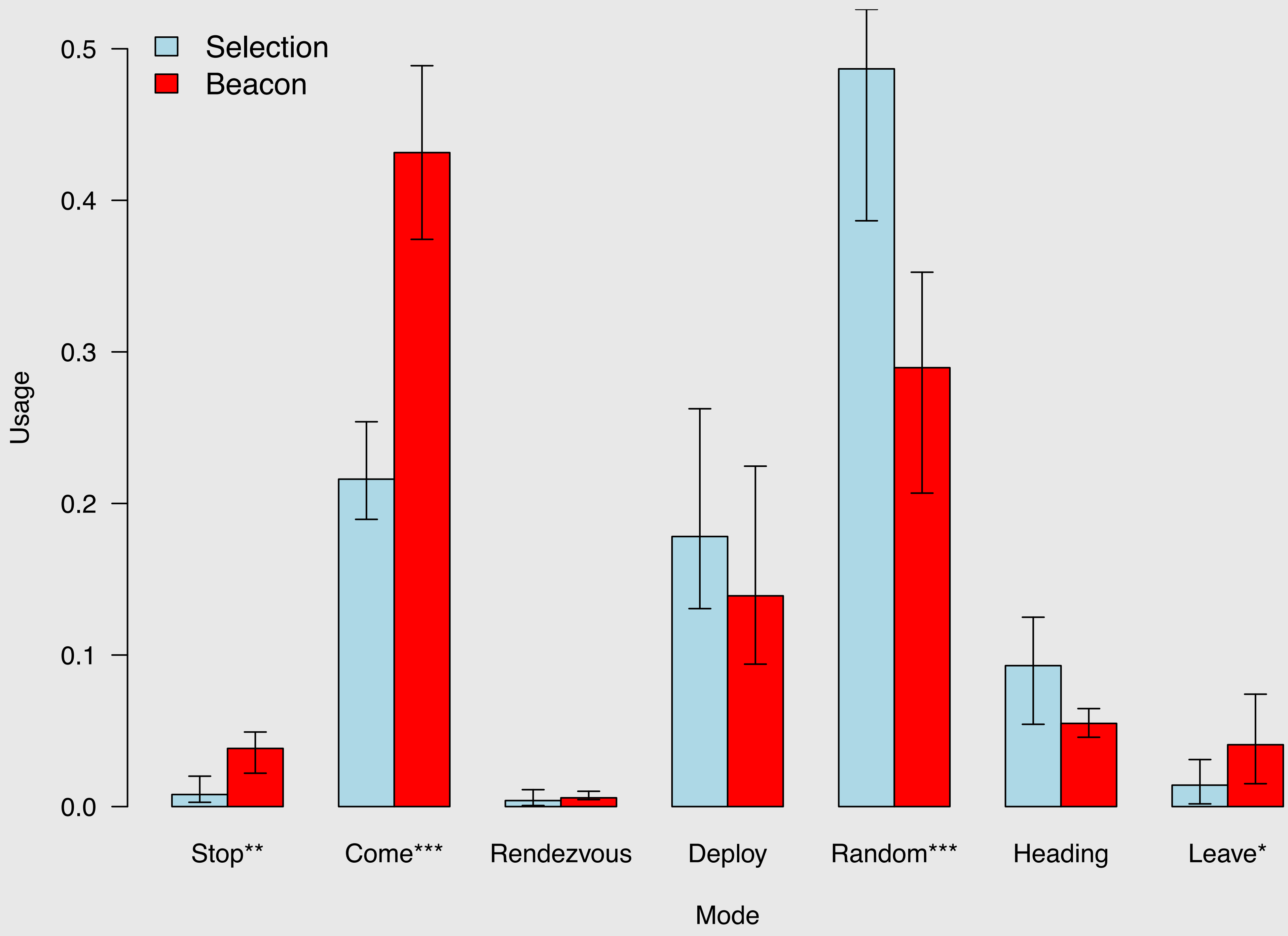


Figure: Performance of operators (32 participants) in two control regimes and a simple mission-specific autonomous swarm across a variety of environments. Operators successfully adapted to more complex and challenging environments in which their autonomous behaviors (deploy and rendezvous) lose performance guarantees. Hence, they mitigated the challenges these environment present. On the whole, the task is challenging for human operators as seen by the superior performance of the autonomous swarm in open environments.

Mode Usage



Selection
Beacon
0.5
0.4
0.3
0.2
0.1
0.0
Usage
Stop**
Come***
Rendezvous
Deploy
Random***
Heading
Leave*
Mode

Scalability

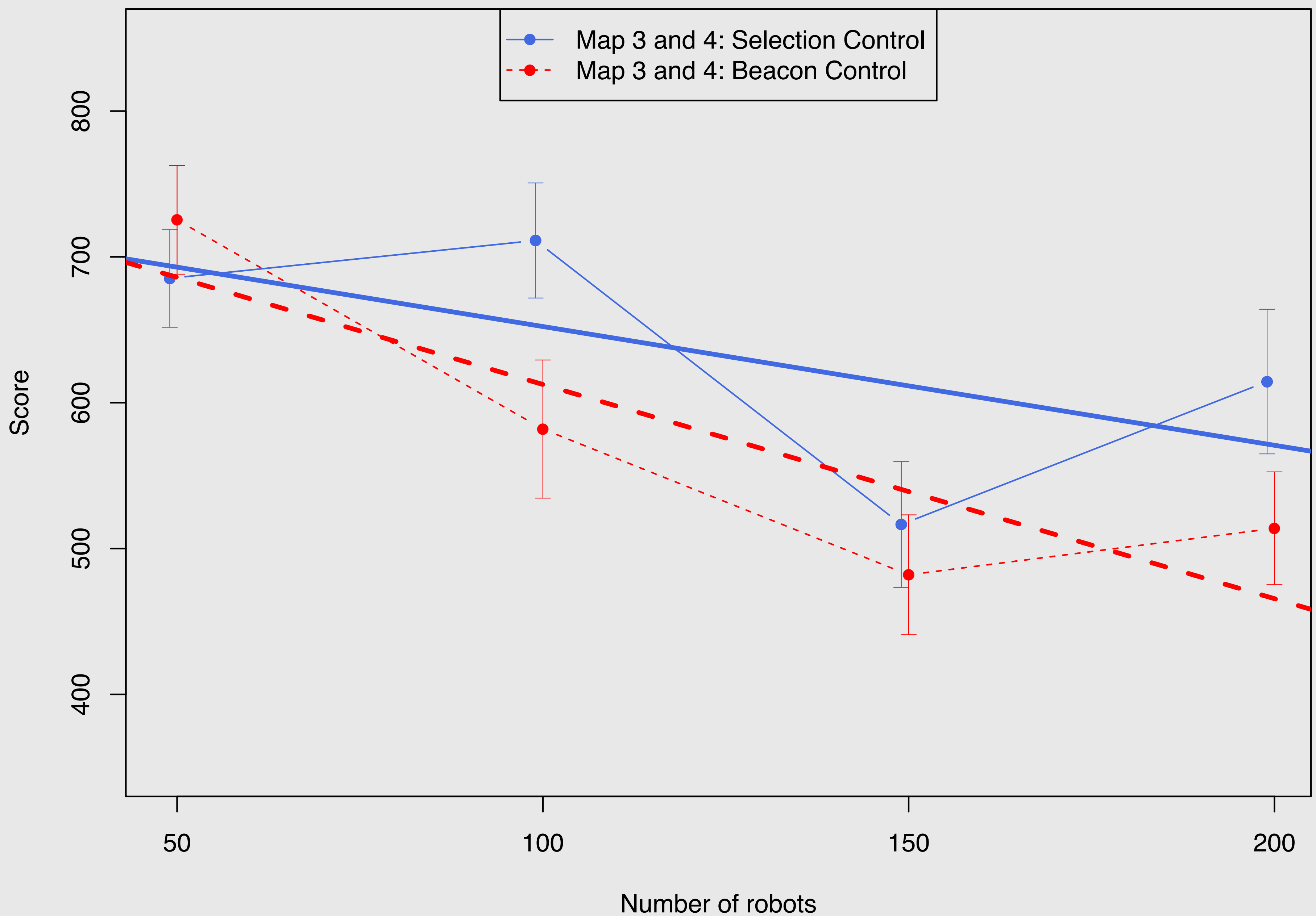
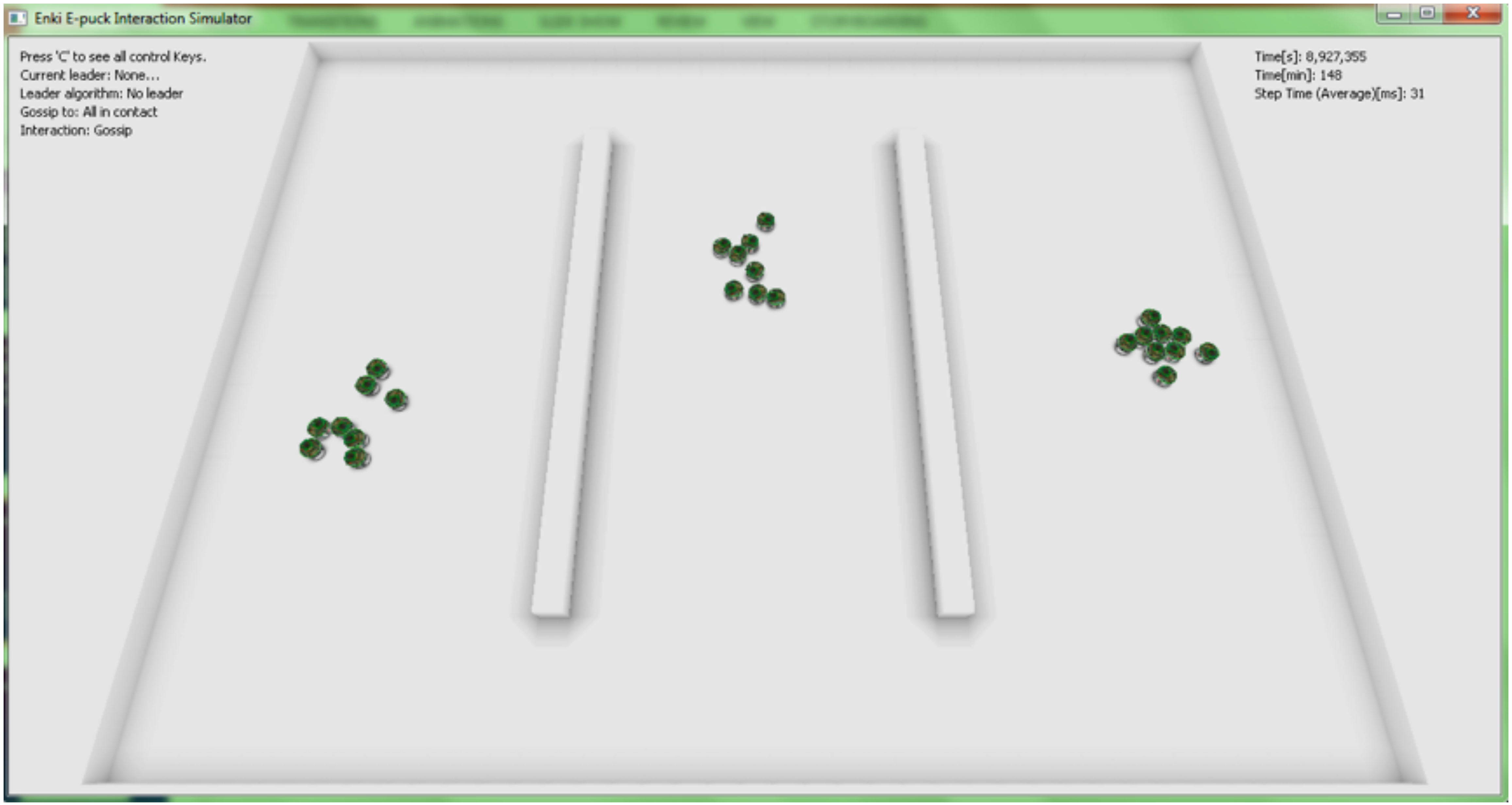


*Figure: Performance as the cumulative amount of information collected by the swarm (regressions lines) across swarms of different sizes but similar overall capability, e.g.: **50 robots with a sensing range of 2m each** compared to **100 robots with 1m each**.*

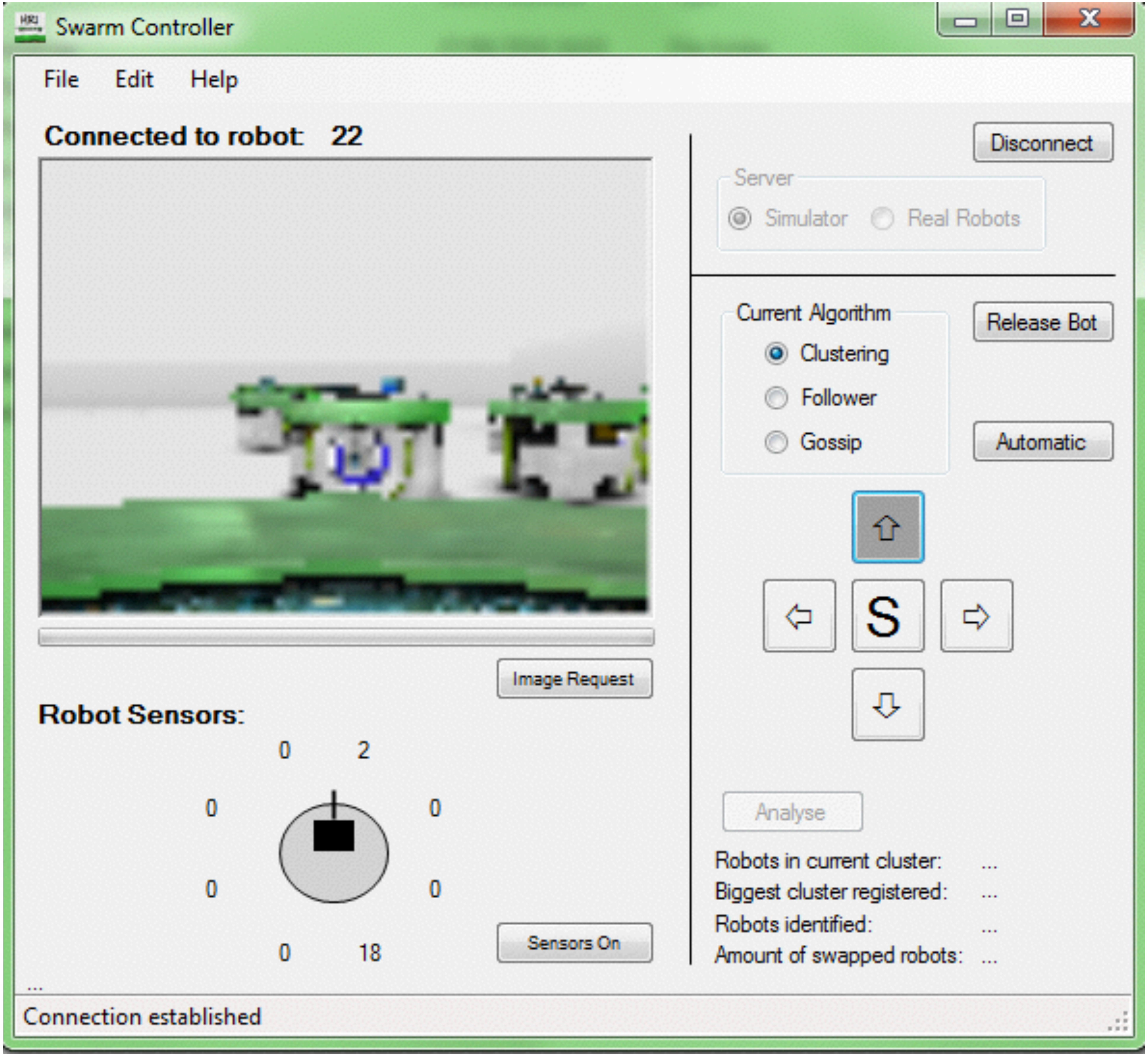
Conclusions

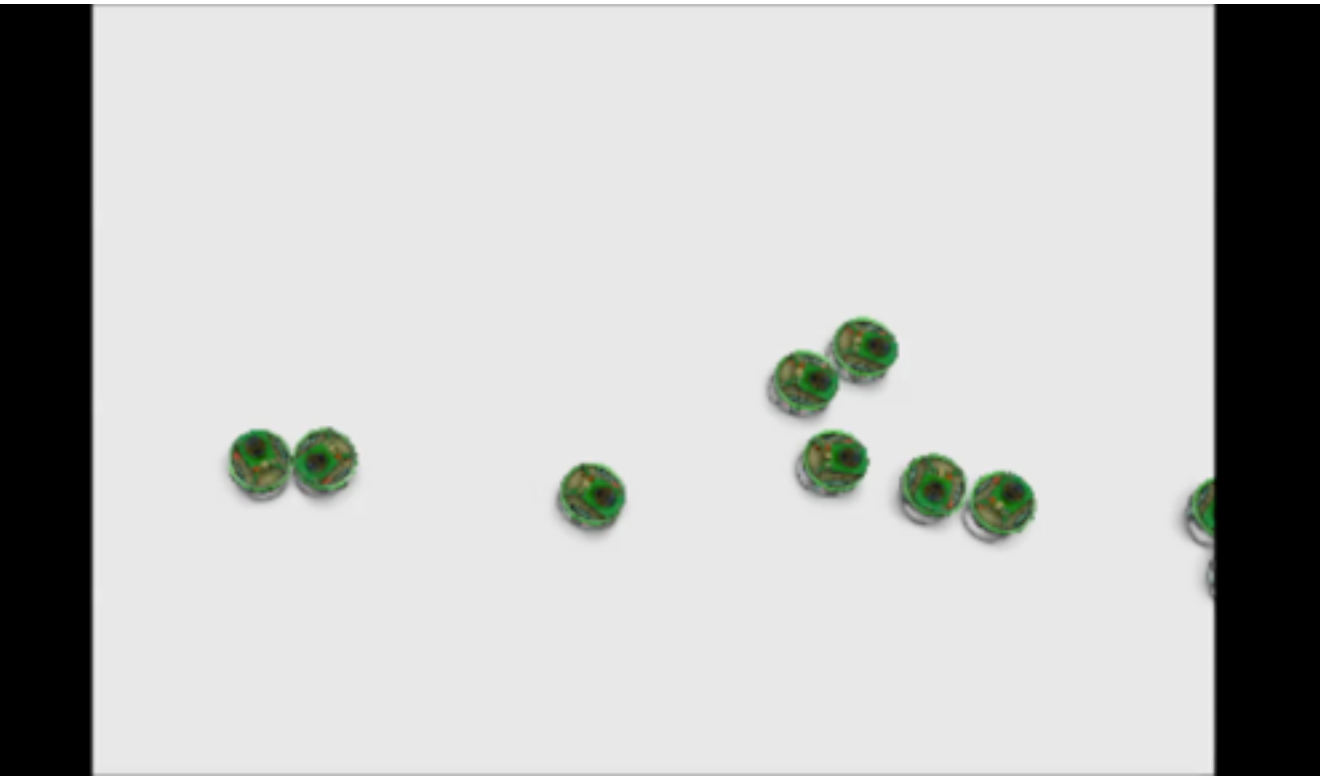
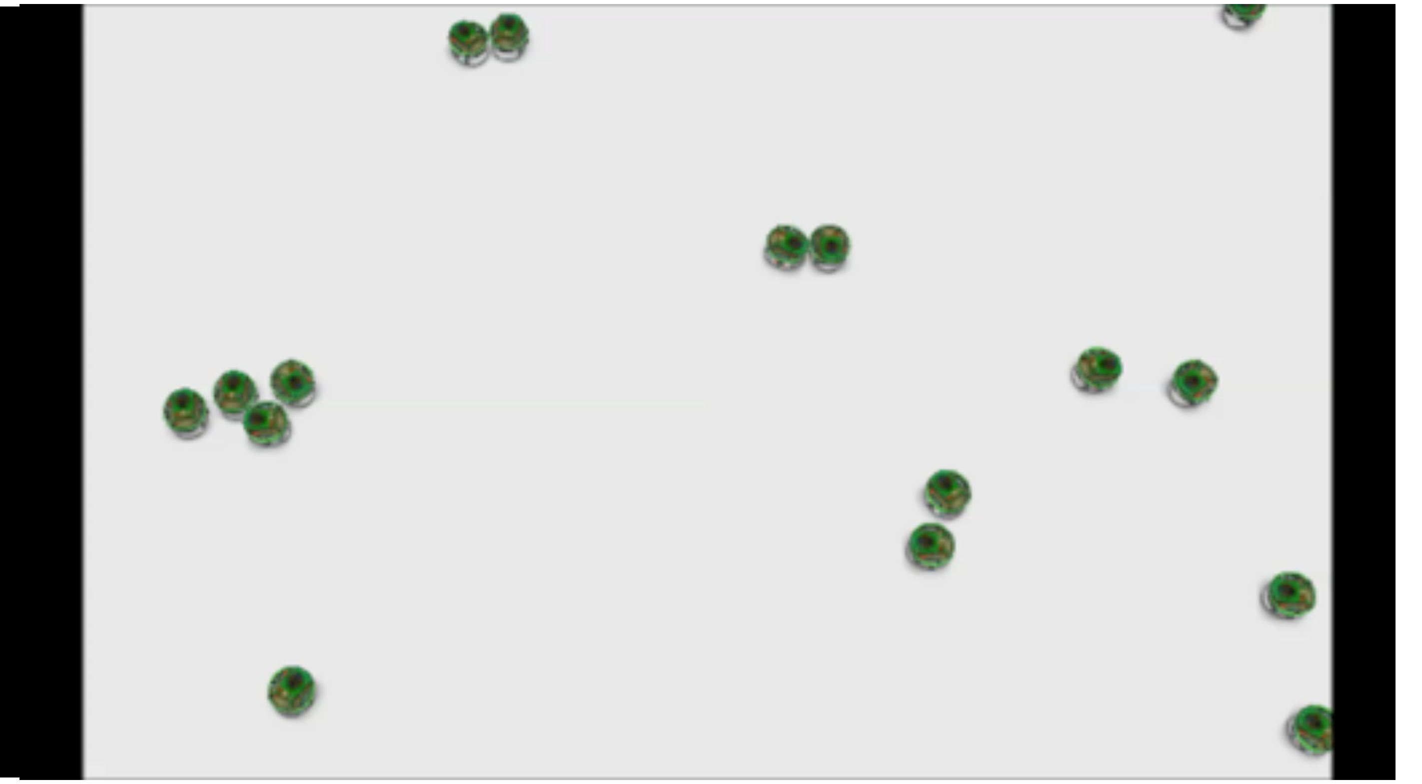
- Operators adapted to complex environments
- Beacon controls, which are **range-based**, are more **difficult** to use
- **Interaction** between control method and available swarm behaviors (group instructions)
- **Effective controllability** is more relevant than scalability

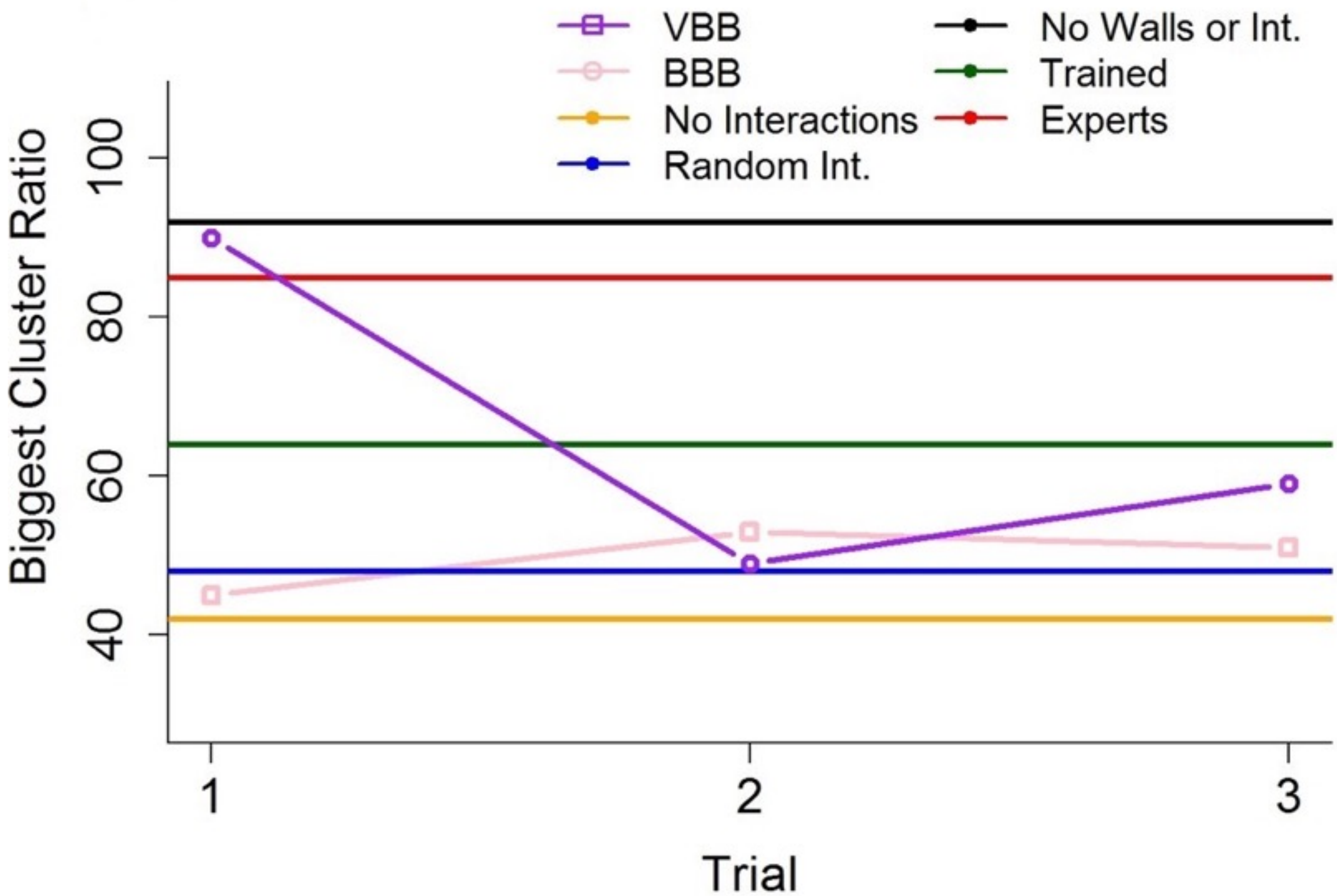
Without Localization



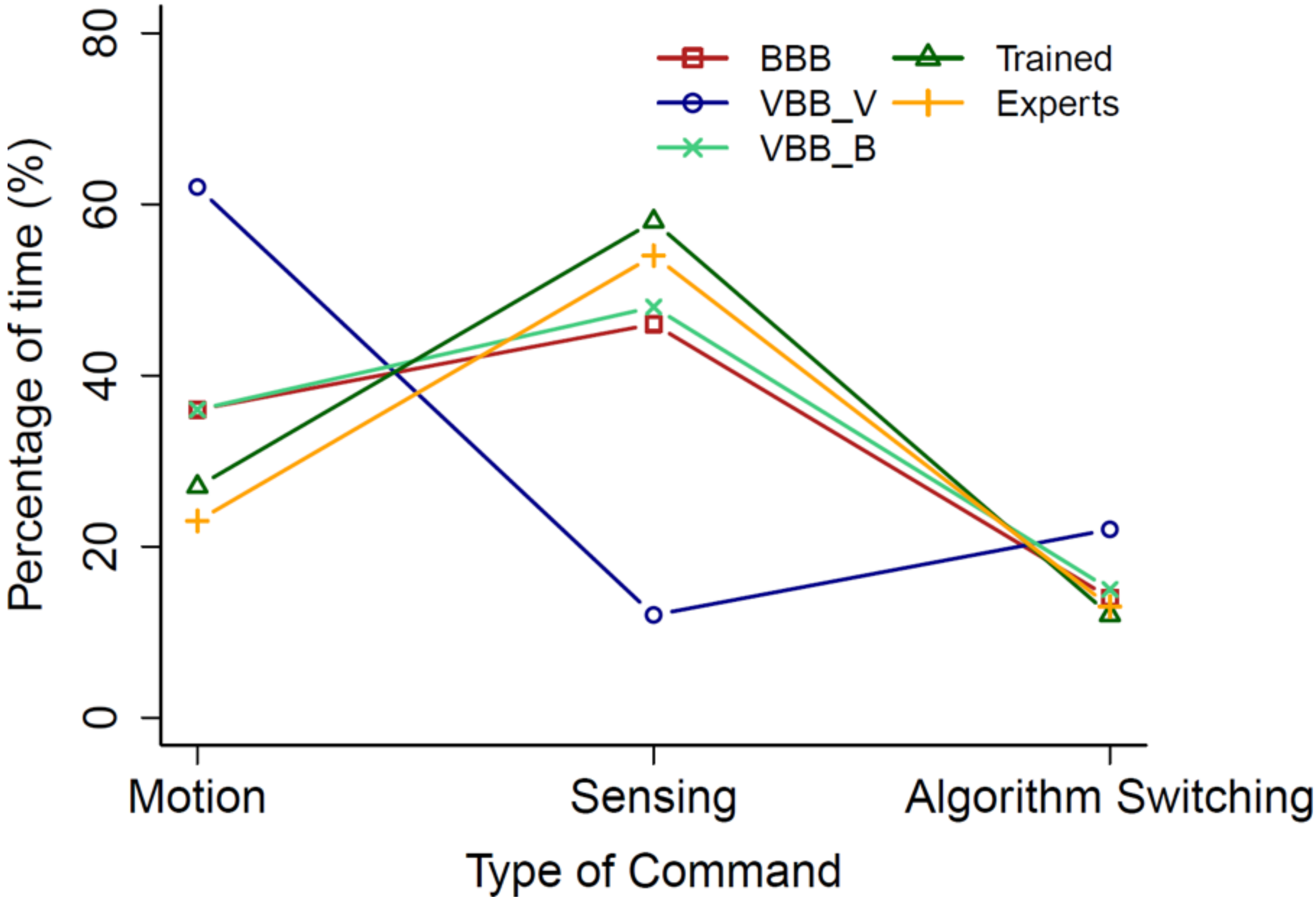
Kapellmann-Zafra, G., Salomons, N., Kolling, A., & Groß, R. (2016, September). Human-Robot Swarm Interaction with Limited Situational Awareness. In *International Conference on Swarm Intelligence* (pp. 125-136). Springer International Publishing.


Swarm Controller
File
Edit
Help
Connected to robot: 22
Disconnect
Server
Simulator
Real Robots
Current Algorithm
Clustering
Follower
Gossip
Release Bot
Automatic
S
Image Request
Robot Sensors:
0
2
0
0
0
0
0
18
Sensors On
Analyse
Robots in current cluster: ...
Biggest cluster registered: ...
Robots identified: ...
Amount of swapped robots: ...
...
Connection established

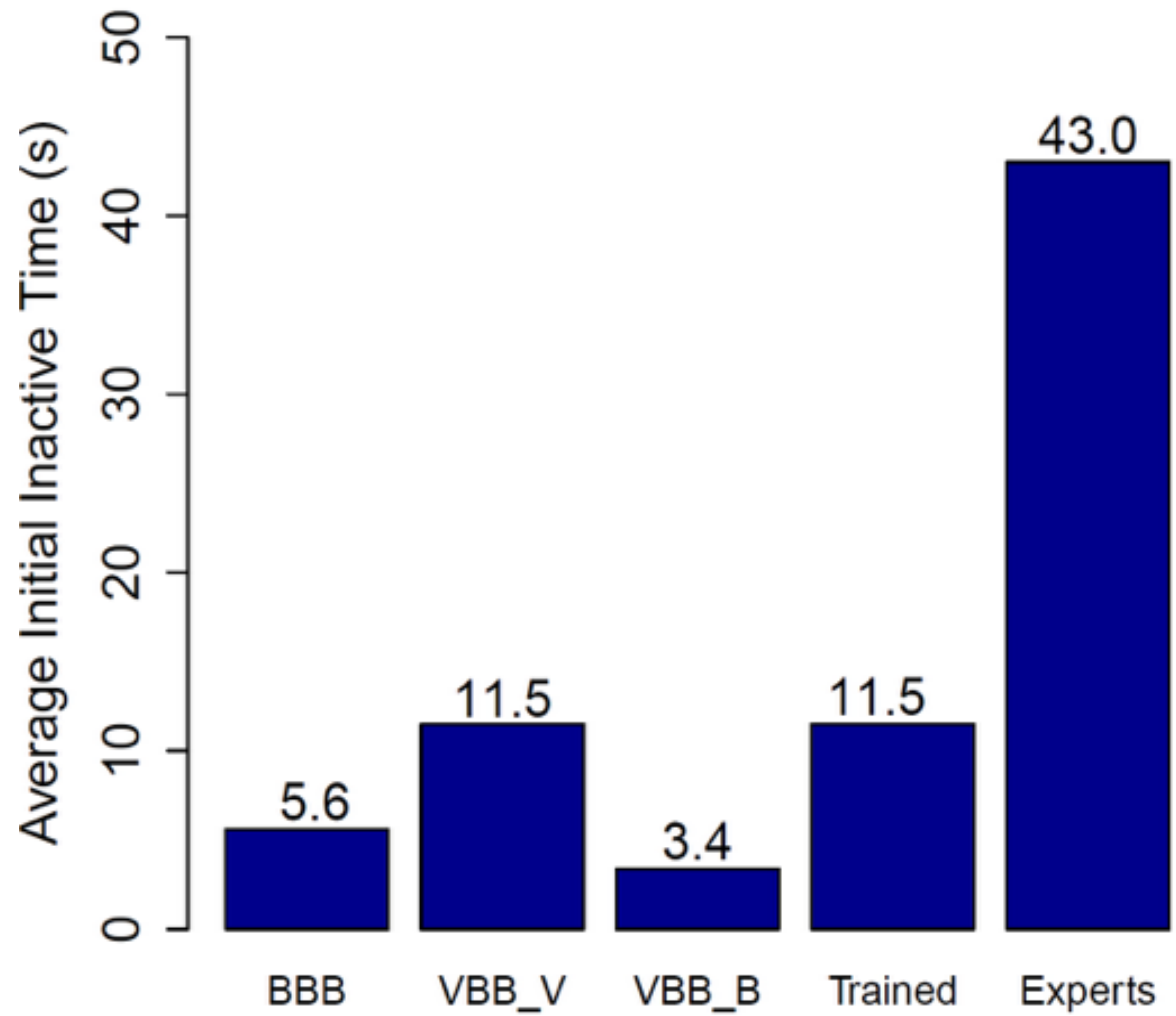



VBB: trial 1 has global visual feedback; 2,3 are blind
BBB: trials 1,2,3 are blind


BBB
VBB_V
VBB_B
Trained
Experts
Percentage of time (%)
0
20
40
60
80
Motion
Sensing
Algorithm Switching
Type of Command

Learned Neglect Benevolence



Conclusions

1. Increased requests for local sensory information; more so for experts
2. Evidence for neglect benevolence for trained and expert operators
3. Exposure to global swarm dynamics did not accelerate the learning process

Further work focuses on detailed analysis of operator behavior and dynamics and individual differences

Final Notes

View the operator also as a disturbance
to the autonomy and system

Opportunity to contribute to basic
research in cognition and neuroscience

Study HSI to understand how to interface with
complex systems — robot villages