Networked Human-Robot Swarms

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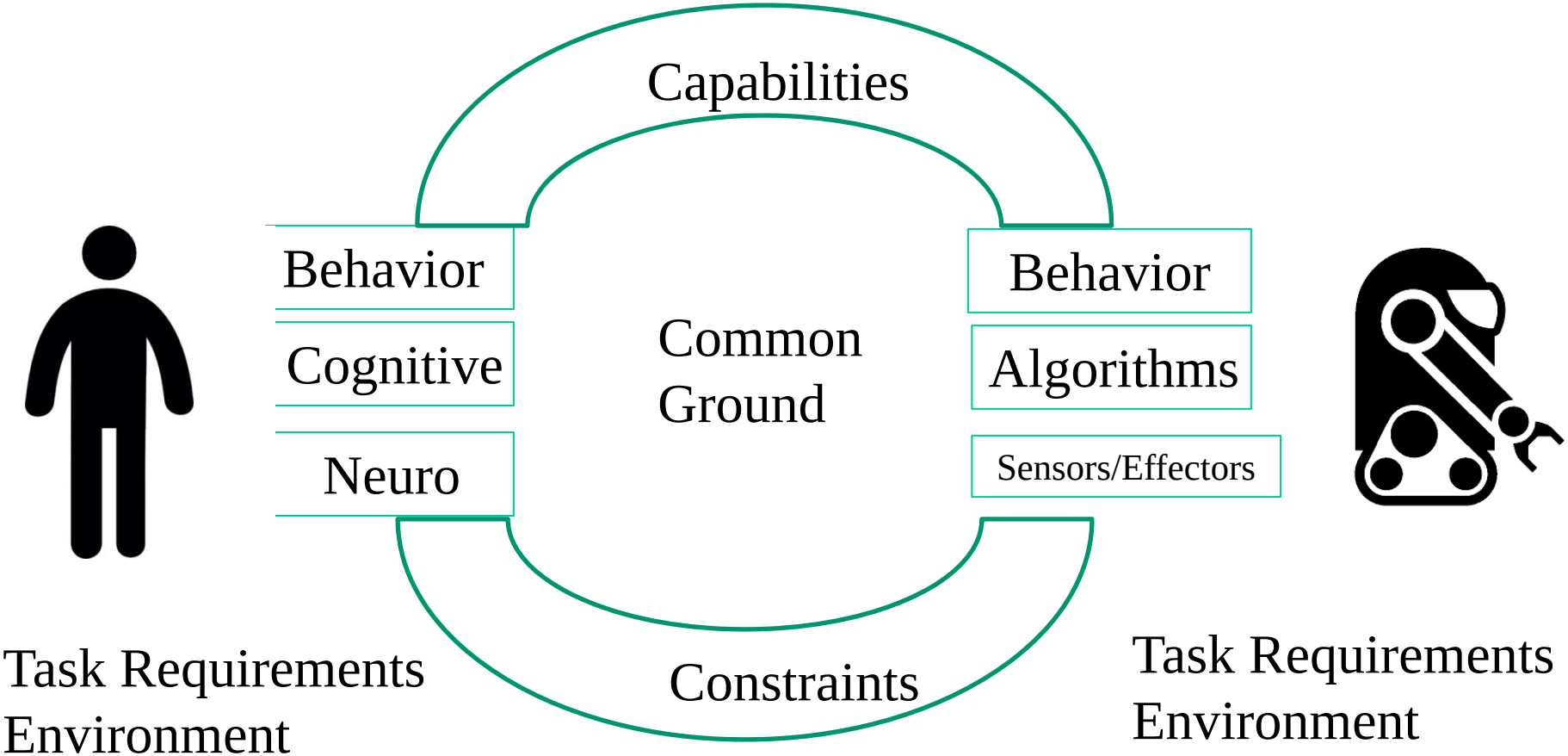
Outline

- Introduction
- Framework for human supervisory control
- Human control of independent robots
- Scheduling of operator attention
- Human control of autonomously coordinating swarms
  - Control via Leader(s)
  - Information leaders
  - Optimal human control input timing
- Conclusions

HRI Centered Co-Development



Task Requirements
Environment
Mental Workload
Affect
Learning

Mutual predictability
Trust
Synchronization

Task Requirements
Environment
Hardware
Algo Scalability
Learning

Why human control of multi-robot systems?

Recognize & mitigate shortcomings of autonomy

Utilize information inaccessible to autonomy

Human Role

Convey changes in intent an mission

Many forms of interaction are needed

Robots

- must be individually controllable
- must function autonomously for long periods
- must be commandable as cooperating teams
- must adapt to absence of human attention
- must incorporate humans in autonomous plans

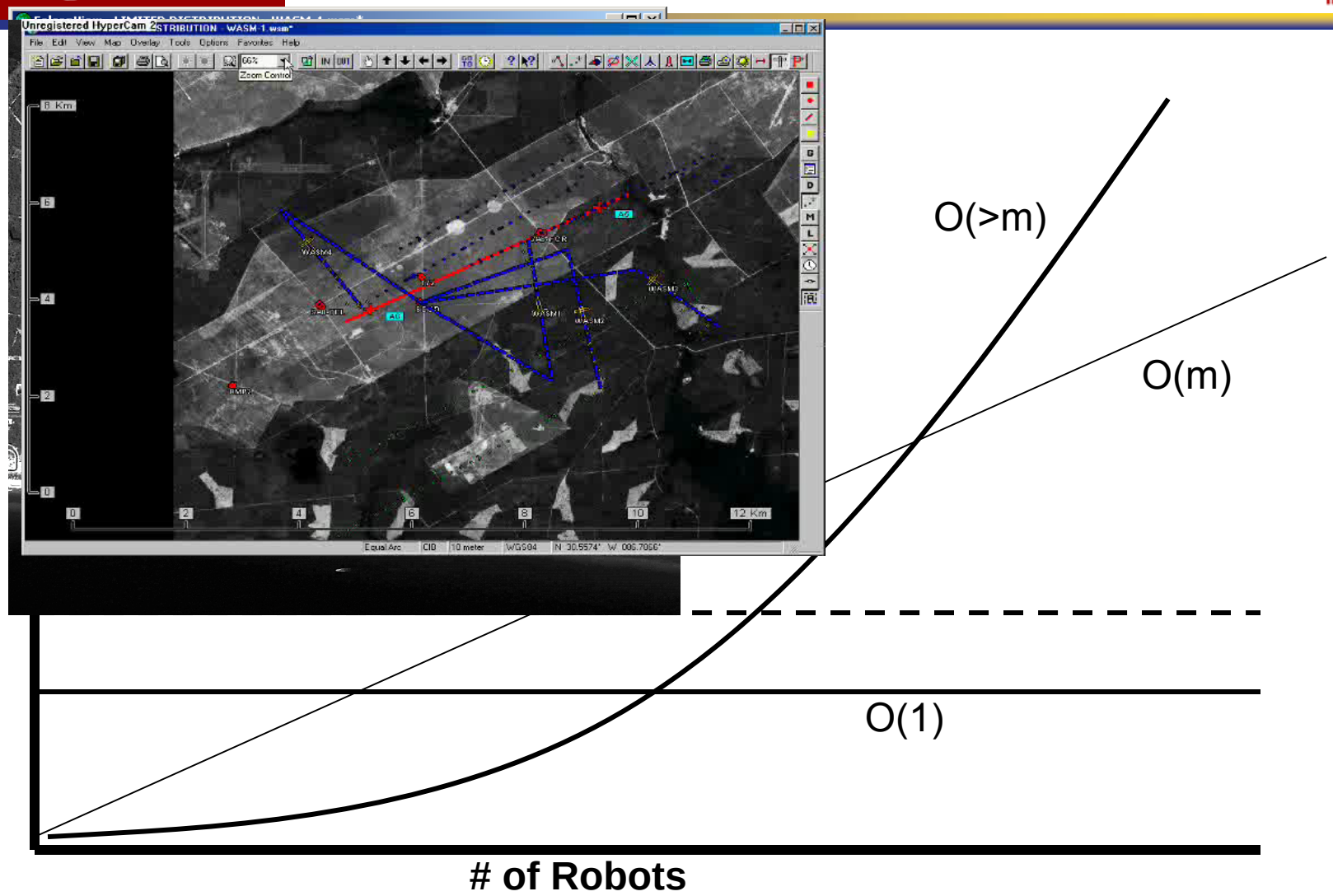
Key Idea: Look at HRI from viewpoint of complexity of operator's cognitive complexity of command

This framework allows systematic study of human control of multi-robot systems

•Neglect Tolerance Model (NTM)—for O(n) control

•Bio-inspired swarms—for O(1) control

As size grows, complexity of command dominates



Scheduling Human Attention to Improve HRI Performance

Improving O(n) performance

Robots act independently of one another

1.Xu, Y. Sheller-Wolf A. Sycara, K The Benefit of Introducing Variability in Quality-based Service Domains, *Operations Research*, Vol 63, issue 3, Jan 2015

2. C.hien, S., Wang, H. Lewis, M. & Sycara, K..Effects of alarms on control of robot teams*, Human Factors and Ergonomics Society (HF ES)* vol. 55, no.1.,2011

2. C.hien, 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

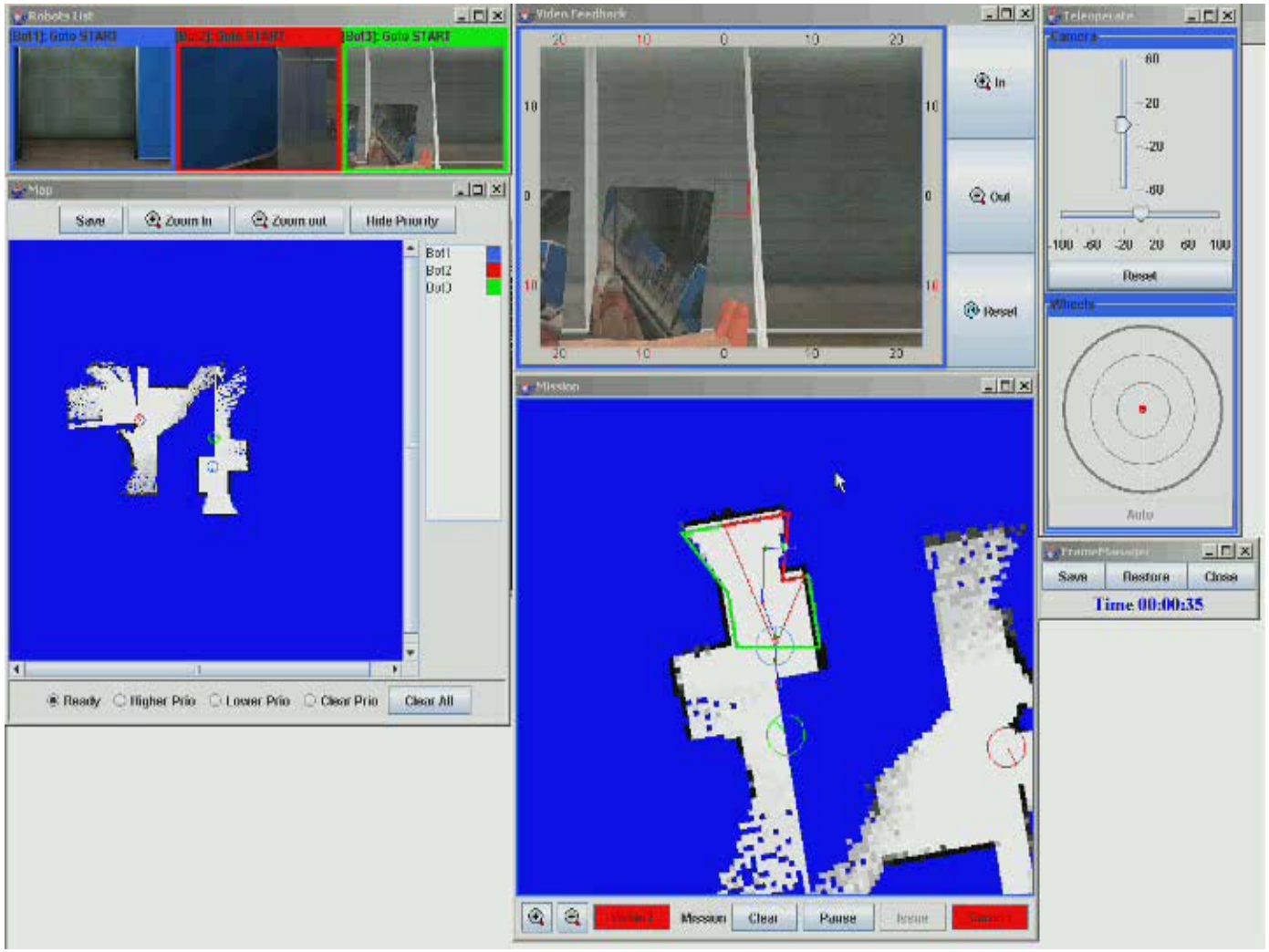
Independent Robots

- Neglect Tolerance: Most autonomous systems require some degree of interaction (interaction time IT) with a human operator to achieve a desired behaviour.
  - Assumption: If system is neglected, its performance will decrease BUT for robot swarms, neglecting the swarm, i.e. delaying control input, may increase swarm performance.
- The rest of the time the operator can neglect the system (neglect time NT)
- Cognitive factor: limited human attention that must be allocated
- Multiple robots that operate independently
  - Number of robots an operator can interact with is:

$$\text{FanOut} = \mathit{floor}\left(\frac{\text{NT}}{\text{IT}}\right) + 1$$

  - This is an upper bound, many practical limits
  - Our studies in search and rescue have shown this number to be 8

Typical MrCS interface



fan-out =

Can Operator Attention be Scheduled?

+ 1

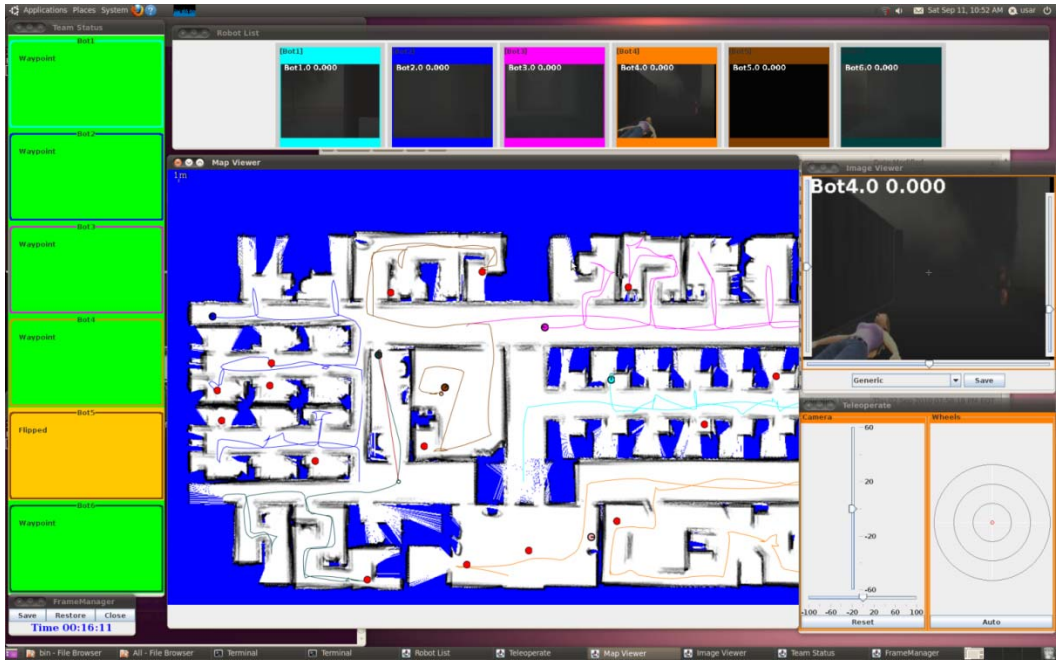
Operator must **both** search and **mark** victims (primary task M') that appear at rate λ and maintain robots' status (secondary task, M)

Attention direction via FIFO or alarms

- Monitoring M could be eliminated

$$FO = \frac{NT * \left(1 - \frac{M' + IT'}{\lambda}\right)}{M + IT} + 1$$

We changed architecture to give each robot **self-reflection**.



- Robots **monitor themselves** and alert the operator when they need attention
- Operator is **Server** and robots **Clients**
- Robot alerts are displayed in **FIFO Queue** to direct operator attention

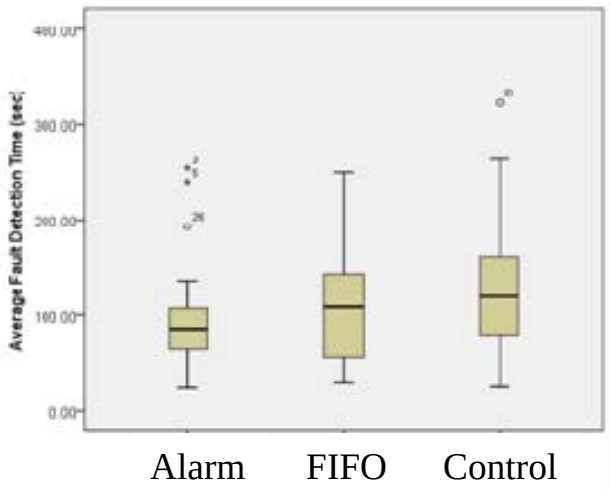
or

- **Alarm** panel showing all robots reporting failures

Attention Guidance Experiment 1

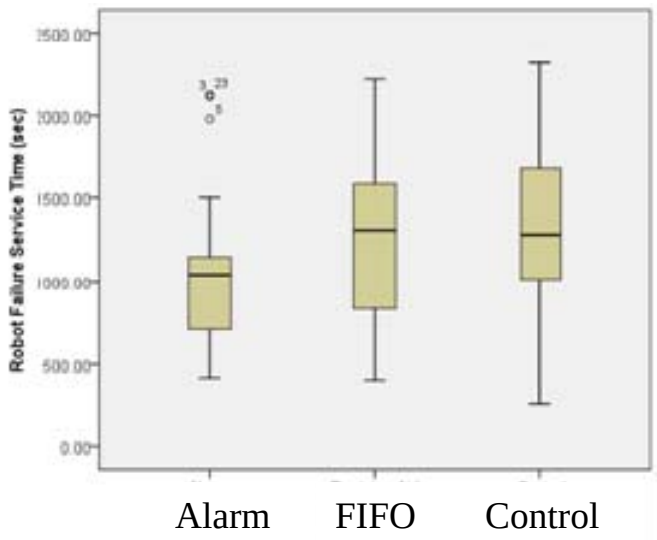
Faults "repaired" sooner

Select robot-to-repair sooner

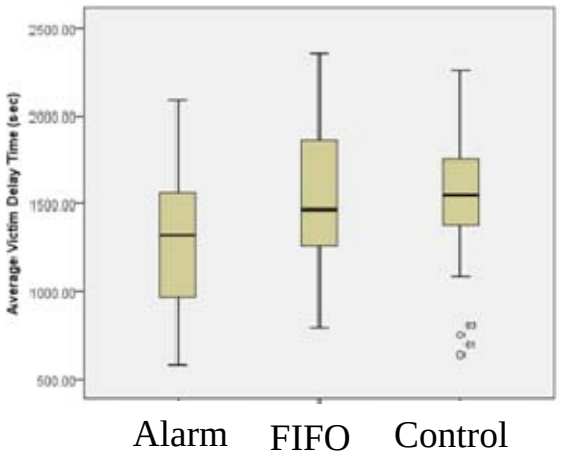


Ordering:

1. Alarm
2. FIFO
3. Control



Victims detected sooner



Because failures are homogeneous FIFO and Alarm conditions should be equivalent if operator's attention can be effectively directed

Conclusions

- Alerting operator to failures improved performance
- Directing attention (FIFO) to a particular robot was less effective than merely alerting

Experiment 2-Operator attention CAN be scheduled to improve performance

Heterogeneous Failures

Failure	Description	Time to Resolve
Stuck	Robot was stopped by approaching obstacles	short
Teleop Lagged	Robot executed operator's command with 2~3 seconds delay	intermediate
Camera Sensor Failed	Robot's video feed was frozen right before the failure happened	short
Map Viewer Failed	**Robot's position on the map viewer unable to update**	**Long**

Shortest Job First (SJF) discipline yields maximum throughput

Experiment compared:

- SJF queue
- FIFO queue
- Alarm

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

SJF performance did not differ significantly from the BEST performance on measures

- SJF and Alarm best on:
  - Latency to resolve failures
  - Time between selecting and fixing failure
  - Failures resolved
- SJF and FIFO best on:
  - Missed victims
  - Mental workload

Evidence for Cognitively Efficient Task Switching

- Experiment 1:
- If attention can be directed, because time/effort are the same across failures, then Alarm = FIFO
    - However, experiments show Alarm > FIFO
- Experiment 2:
  - If SJF discipline is followed, more robots will be repaired for a given level of interaction. Therefore we expect SJF > Alarm or FIFO
  - Operators in Alarm condition did not follow SJF
    - However, Result SJF~Alarm, and SJF or Alarm > FIFO
- Scheduling attention improved performance but NOT to the extent predicted

Scalable Control Regimes for Robot Swarms

One Human Multiple Robots: Robot Swarms

- When number of robots scales by orders of magnitude single operator cannot control the robots individually
- The robots must coordinate autonomously and be controlled as a group
- We envision large number of autonomously coordinating robots (swarms)
  - Limited capabilities
  - Simple local rules (attraction, repulsion, cohesion)
  - Complex emergent behavior (e.g flocking)
- Main benefits
  - Simplicity of implementing control laws
    - Robots only use information about direct neighbors
  - Scalability of system
    - Swarm is robust to attrition (or addition of robots)

Human Control via Robot Leaders

1. Explicit Leadership

   Human influences swarm through control of a leader whose status is recognized by other swarm members and propagated (token) along with the influence

   switching, behavioral parameters, triggers

Distributed Robotics

influence through recognized leader(s)

2. Tacit Leadership

   Human influences swarm by controlling member(s) who then influence others but without any indication that influence originated with a "Leader"

Bio-Inspired

Influence without leader recognition

Research Study

A comparison between Explicit and Tacit leaders in influencing swarm consensus

Quality Measures

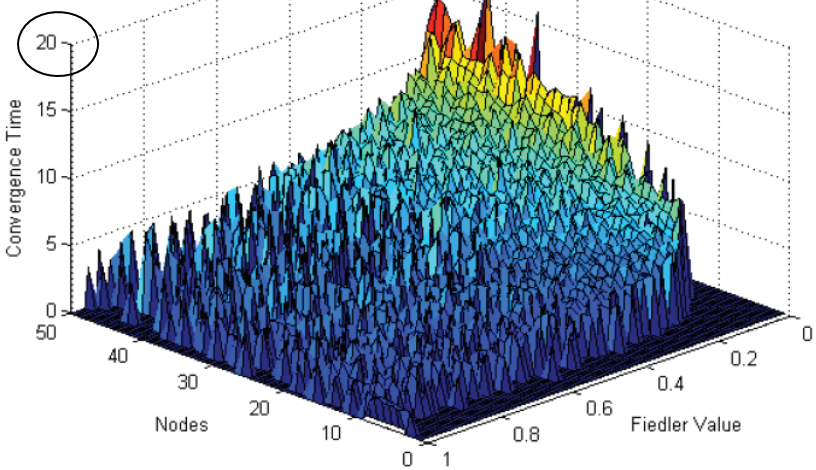
- Convergence time
- Robustness (noise tolerance)
- Effects of graph structure (size and connectivity) on convergence time
- Effects of swarm's movement (changing connectivity graph) on convergence conditions

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.

Flooding (Explicit) vs. Consensus (Tacit)

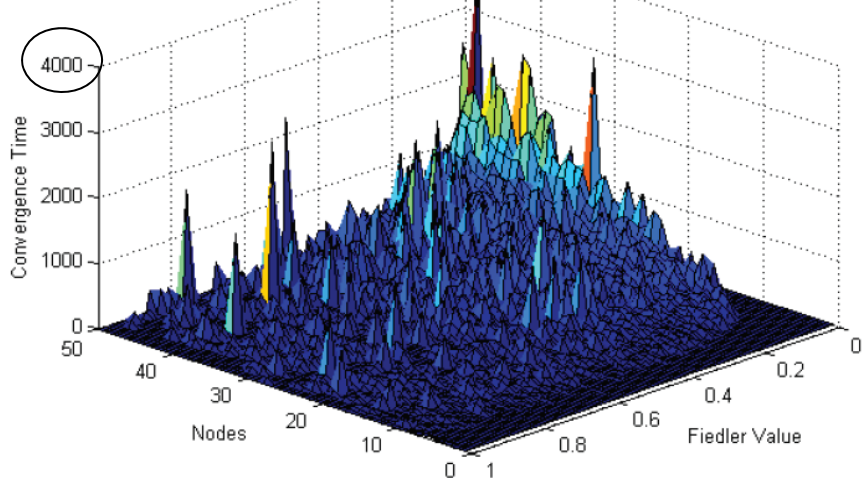
Flooding

20 iterations

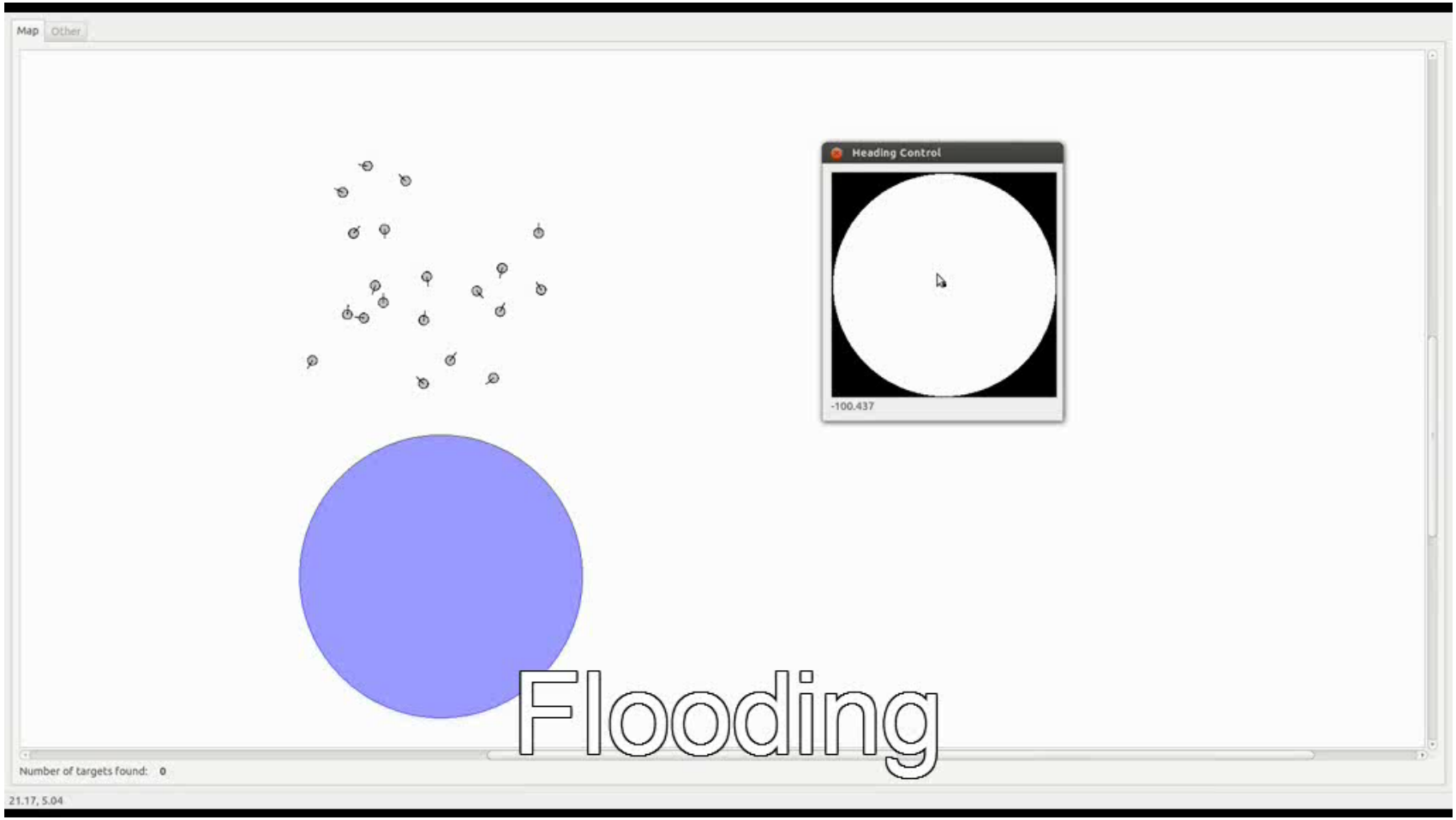


Consensus

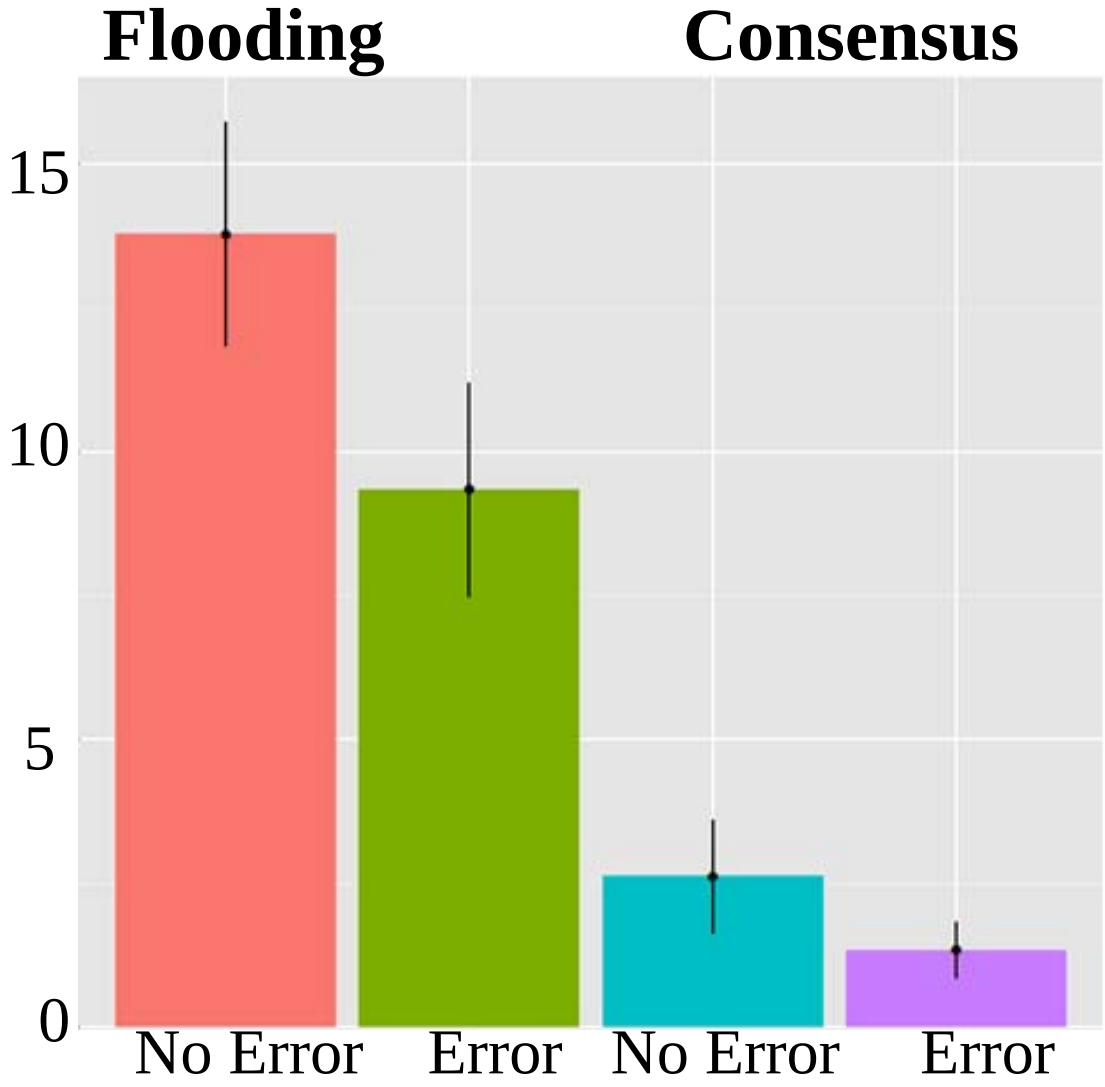
4,000 iterations



Experiment Environment

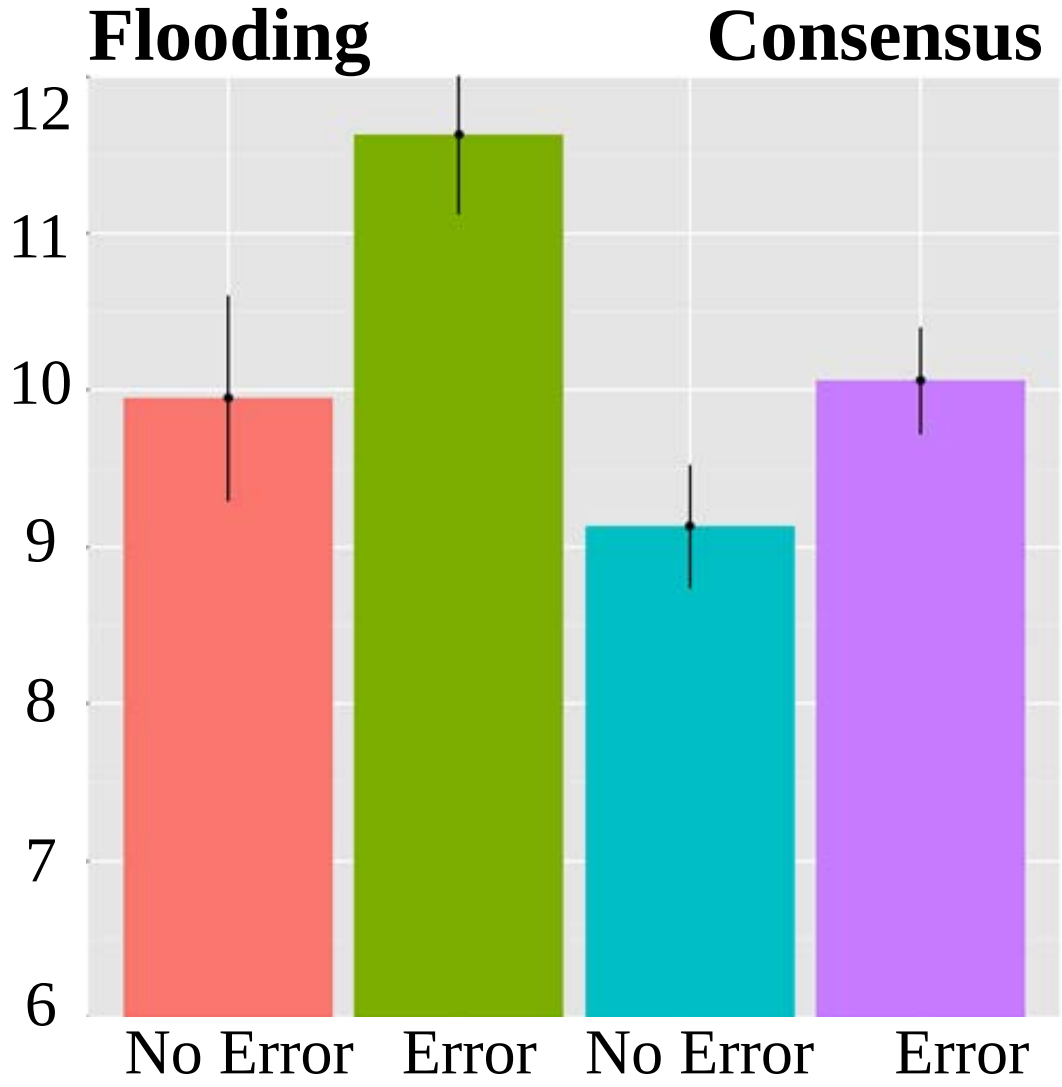


Goals Reached



Swarm Diameter

Diameter is significantly larger for Flooding with Error and smaller for Consensus without error



Advantages/Disadvantages

Tacit Leader(s)

- Closer adjustment to local conditions
- Error tolerance

Explicit Leadership

- More accurate alignment with intent
- More rapid convergence
- May loose resilience associated with distributed coordination

Gesture Control of Swarms

Gestures recognized by Myo arm band

(a) Double Tap (b) Fist (c) Spread Fingers

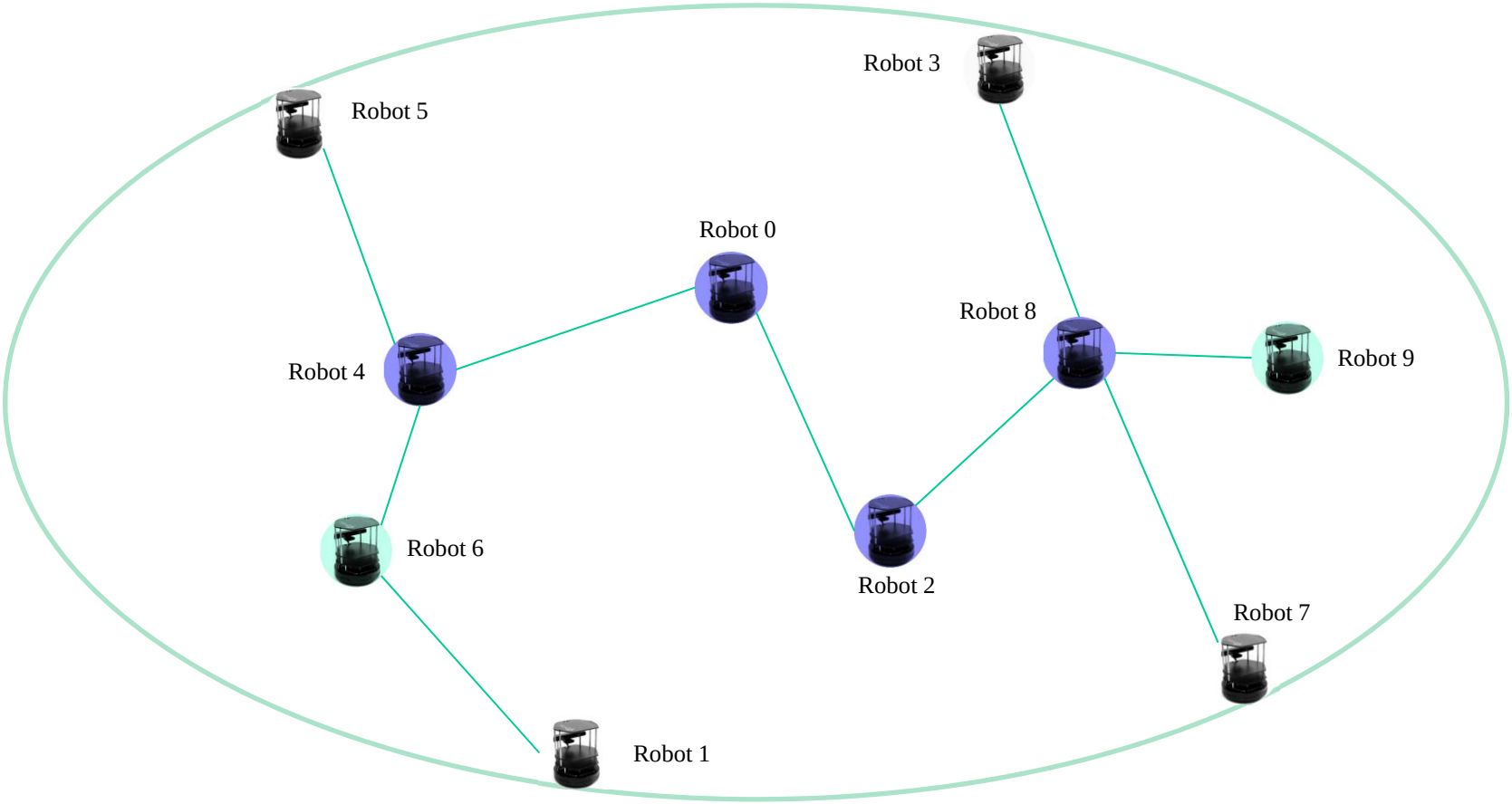
(d) Wave In (e) Wave Out

Selecting Information Leaders for Robot Swarm State Estimation

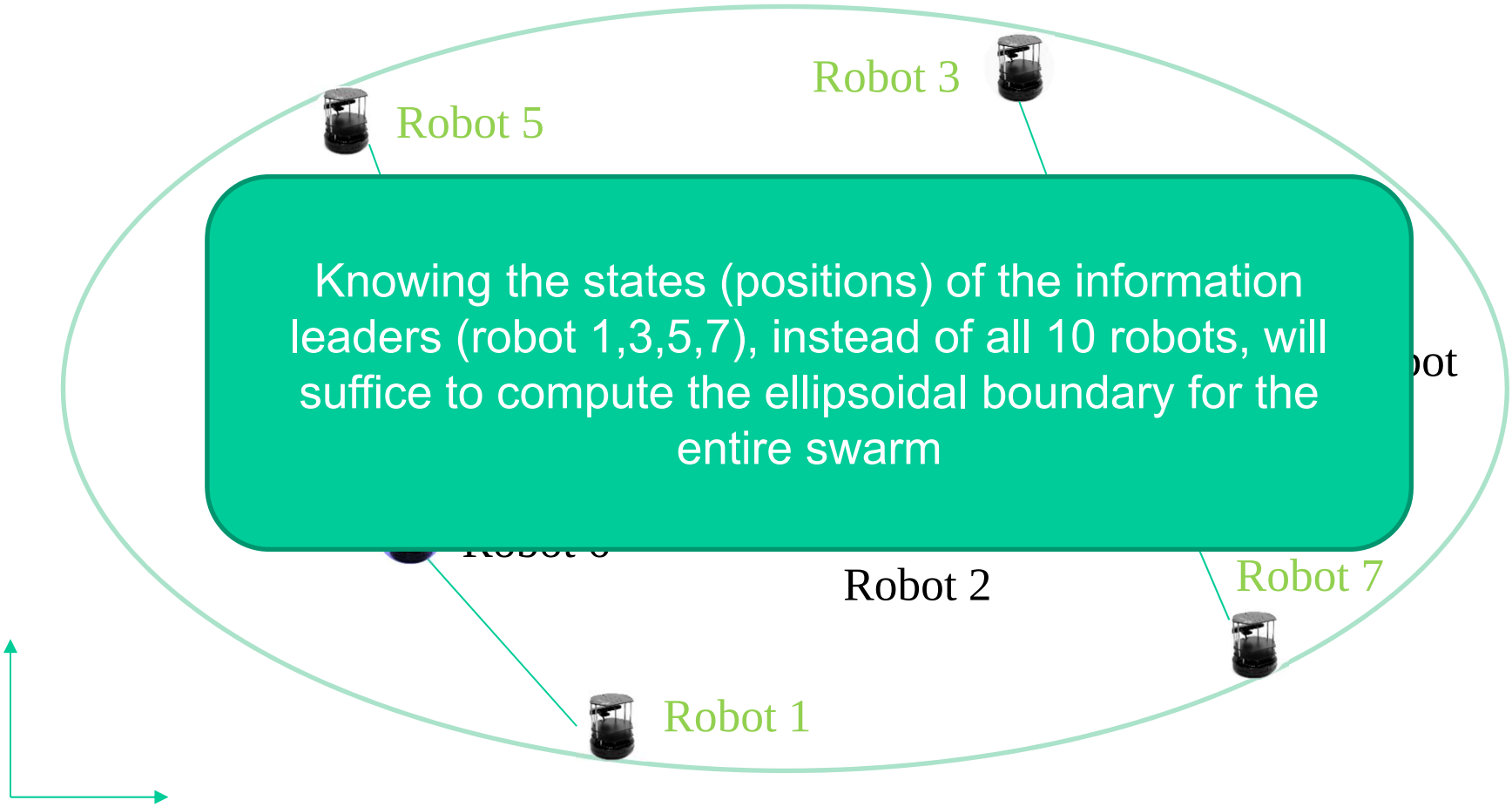
Swarm Intelligibility

- Swarm communication to human must enable human to estimate swarm state in realistic environments (dynamic changes, communication constraints, robot error localization etc)
  - Swarm calculates in distributed way min set of information leaders
  - Core set – any subset of points whose MVEE is a good approximation for the MVEE of all the points
  - Core set is best since number of core set members d(d+3)/2 is invariant to total number of robots in the swarm

- Li, A., Luo, W., Nagavalli, S., Chakraborty, N., Sycara, K. Handling State Uncertainty in Distributed Information Leader Selection for Robotic Swarms, IEEE SMC 2016, Budapest, Hungary, October 9-12, 2016
- Luo, W., Khatib, S., Nagavalli, S., Chakraborty, N., Sycara, K. Asynchronous Distributed Information Leader Selection in Robotic Swarms, Conference on Automation Science and Engineering (CASE), Gothenburg, Sweden, August 24-28, 2015.
- Walker, P., Lewis, M., Sycara, K. The Effect of Display Type on Operator Prediction of Future Swarm States, IEEE SMC Budapest, Hungary, October 9-12, 2016



Planar swarm of 10 robots. MVEE (turquoise), core set (gray), CH set (gray and green), internal (blue)



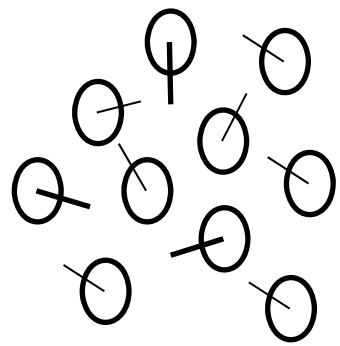
Planar swarm of 10 robots. MVEE (turquoise), core set (gray), CH set (gray and green), internal (blue)

Information Leader Selection

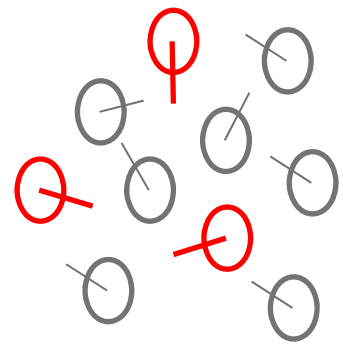
[redacted]

Display Types on prediction of future swarm state

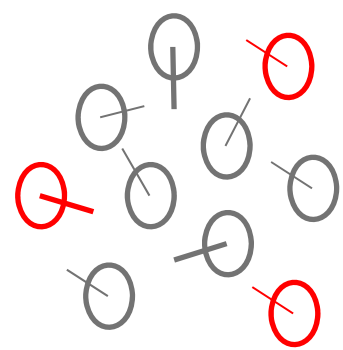
- Different swarm behaviors
  - Rendezvous
  - Flocking
  - Dispersion
- Different visual displays
  - Full information
  - Other
    - MVEE
    - RCC
  - Core set and Ellipse



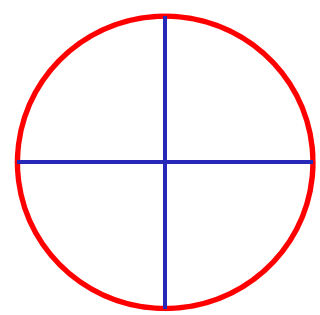
Full information



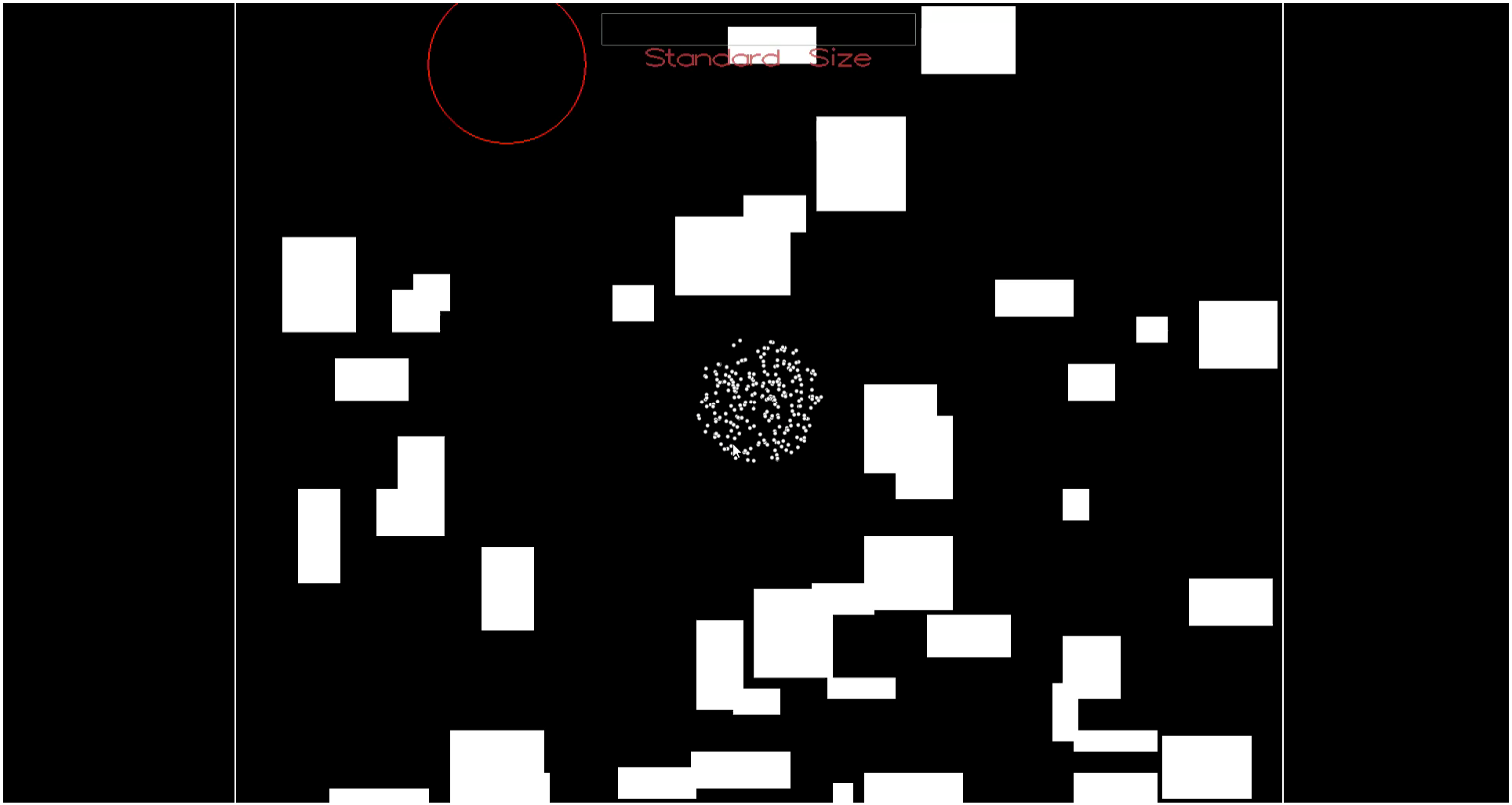
RCC (mixed) Leaders



MVEE (boundary) Leaders

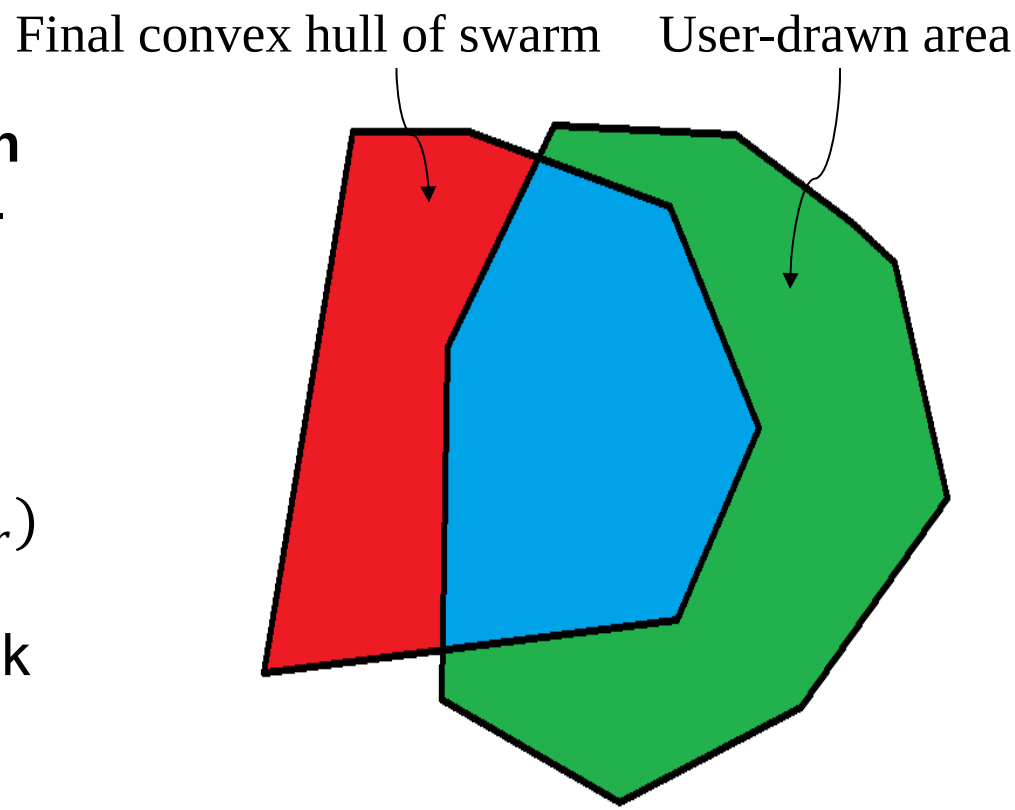


Ellipse


Standard Size

Evaluation Methods

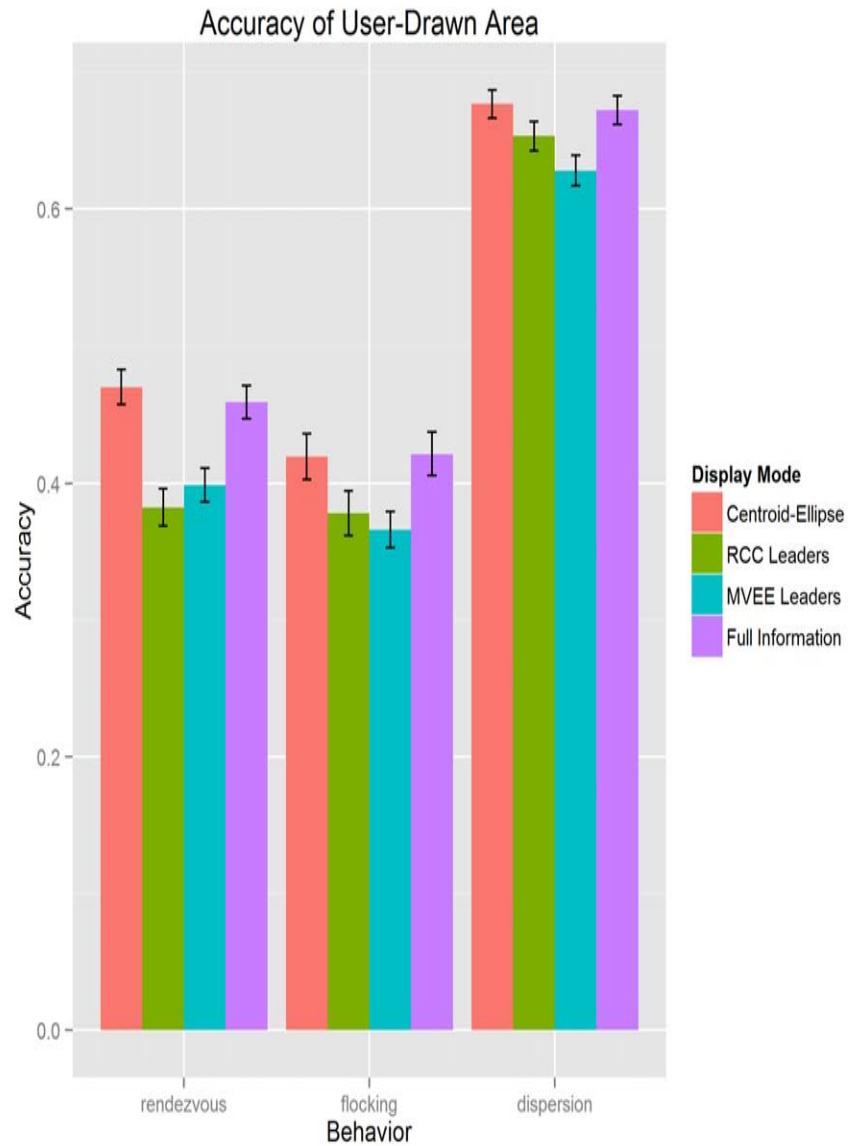
- **Accuracy variable calculation**
  - CH_u: convex hull of user-drawn area
  - CH_r: convex hull of final swarm
  - Accuracy: $(CH_u \cap CH_r)/(CH_u \cup CH_r)$
- **Participant surveys**
  - Participants asked to rank display modes for each behavior type
  - Then, participants asked to rank display modes overall (ignoring behavior)



Accuracy calculation illustration
accuracy = Blue / All

Results Summary

- N = 22, age range 18-65
- **Dispersion** had highest accuracy
  - $F(2,1651) = 414.4$, $p < .001$
  - Explained by size of drawn areas between behaviors
- **Accuracy different for display modes across all behaviors**
  - Rendezvous: $F(3,566) = 11.47$, $p < .001$
  - Flocking: $F(3,589) = 3.355$, $p = .019$
  - Dispersion: $F(3,487) = 4.219$, $p = .006$



Neglect Benevolence-Timing of control input

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

Human Input Timing

- Human must determine timing of input when mission goals change
- Bad input timing may be harmful
- Human experiments with simulated swarms showed that delaying the human input could improve performance
  - Walker, Nunnally, Lewis, Kolling, Chakraborty, Sycara, 2012
  - We termed this phenomenon "Neglect Benevolence" (NB)
- Examples of NB implications for Human-Swarm Interaction
  - Delaying the human input may be beneficial when the desired performance objective is:
    - Minimize time for robotic swarm to reach a goal
    - Have robotic swarm perform a task by a given deadline

- 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
- 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

Motivating Example

Early Input **Appropriate Input** **Late Input**

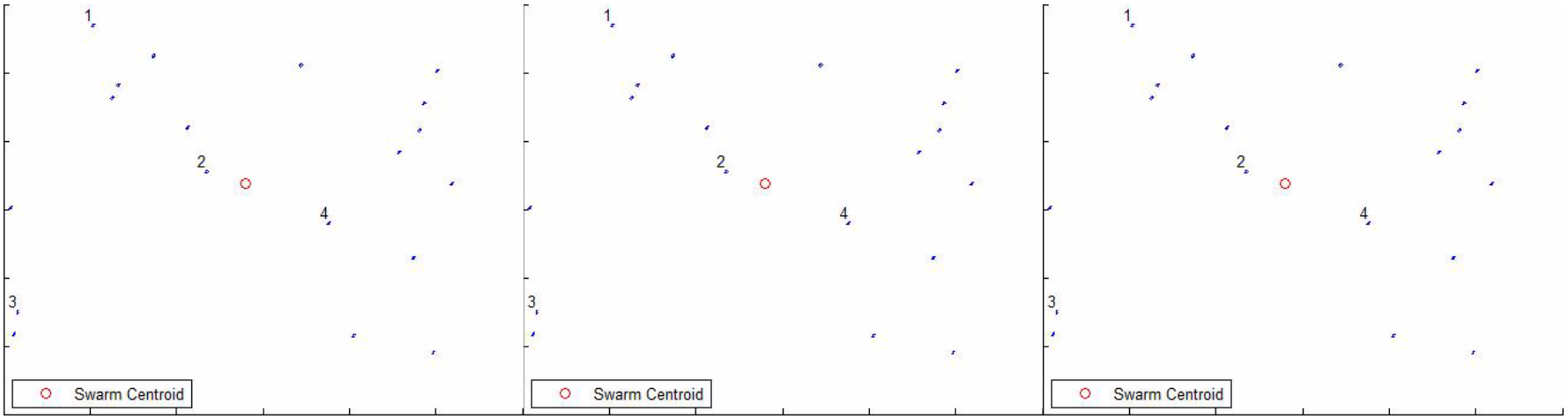
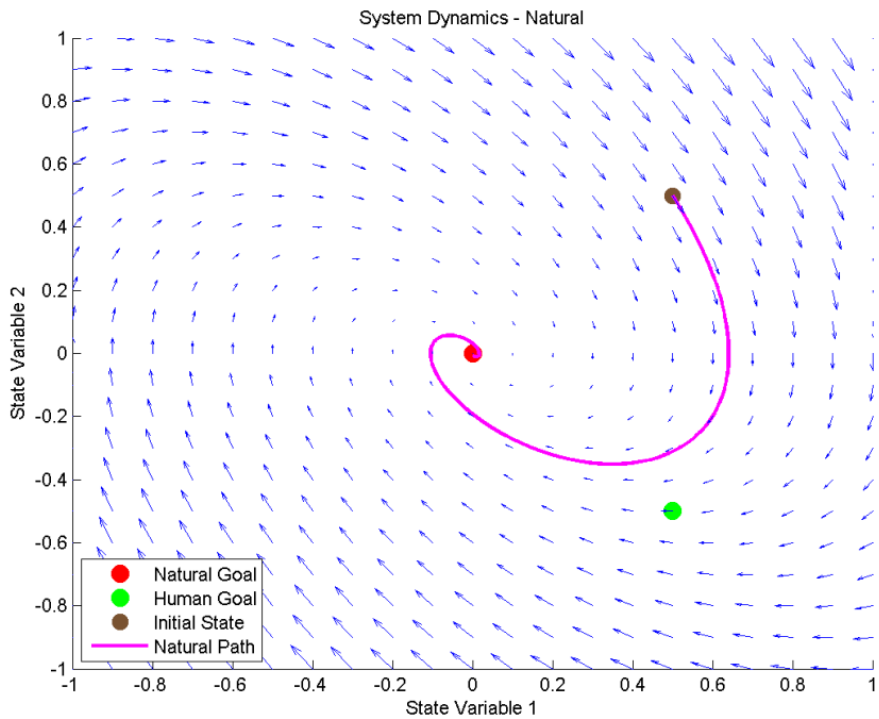
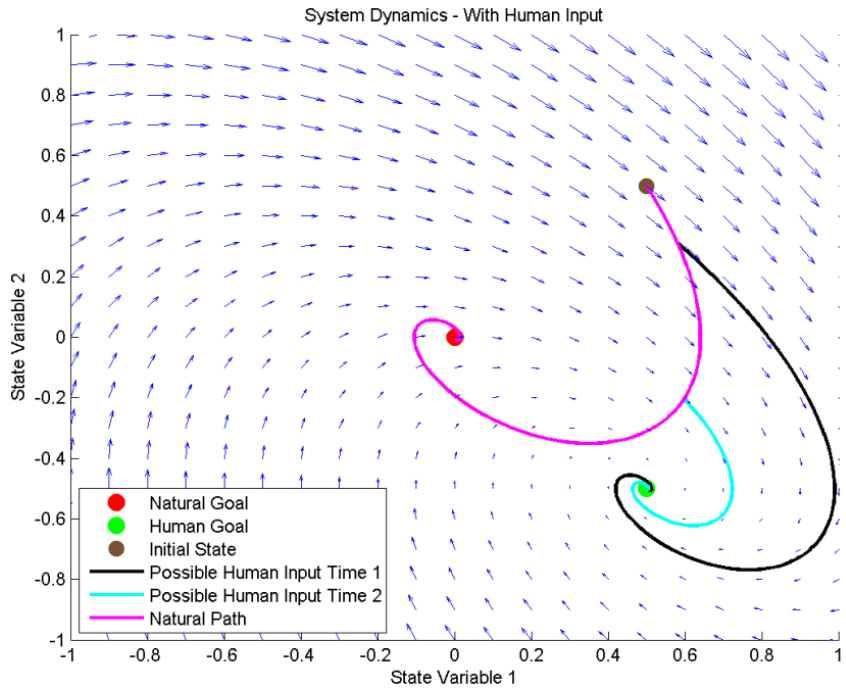


Illustration of Neglect Benevolence in State Space





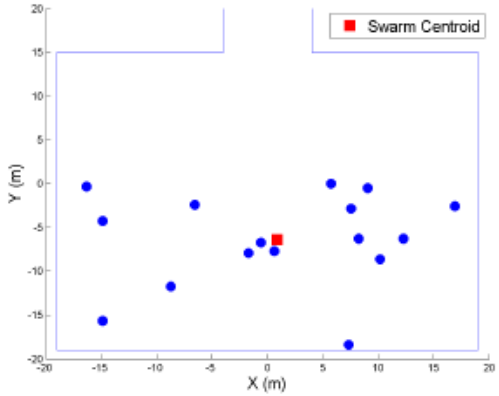
Formalization – Neglect Benevolence

•Given
–System dynamics (including automatic controllers)
–Performance criterion (e.g. time-to-goal)
–One human input : U
–Desired goal states: X
•There may be a subset of states, Xsub where applying the input will decrease system performance
•Each state in Xsub is **Neglect Benevolent**
•If Xsub is not null, the system exhibits **Neglect Benevolence**

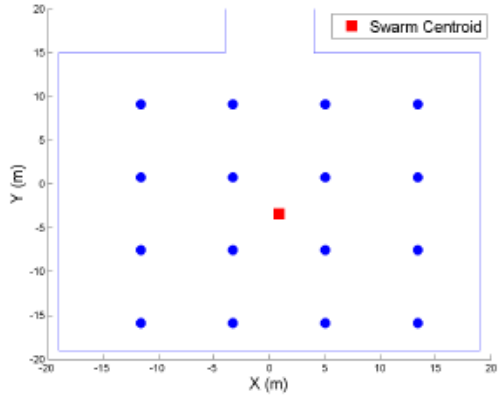
Existence of Neglect Benevolence in LTI Systems

- We proved that all stable LTI systems exhibit Neglect Benevolence!
- Developed Algorithm for calculating optimal time of human input

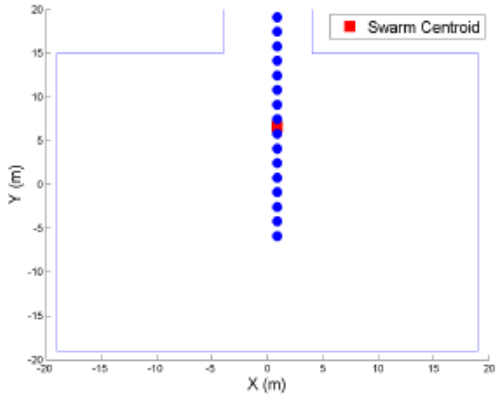
NB in Formation Control of Robotic Swarms



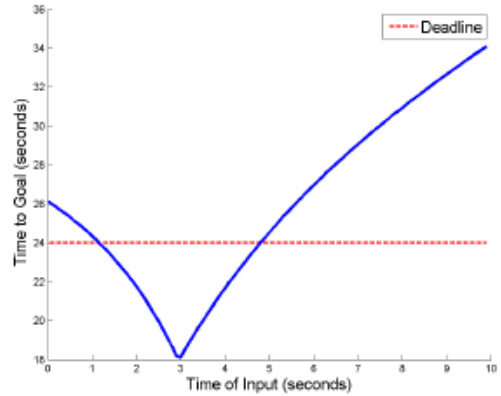
(a) Initial Positions of the Robots



(b) Robot Formation Achieved when No Human Input is Applied



(c) Robot Formation Desired by the Human and Generated when Human Input is Applied



(d) Time at which the Desired Formation is Achieved vs. Time at which Human Input is Applied

Experiments – NB in Formation Control of Robotic Swarms – Robots in Room

Input Applied Too Early (10.0 Seconds)

Input Applied at Optimal Time (20.6 Seconds)

HSI Reference Task

- Neglect Benevolence leads to a formulation of human control of swarms as: *Diverting a swarm's trajectory through state space to some new desired trajectory*

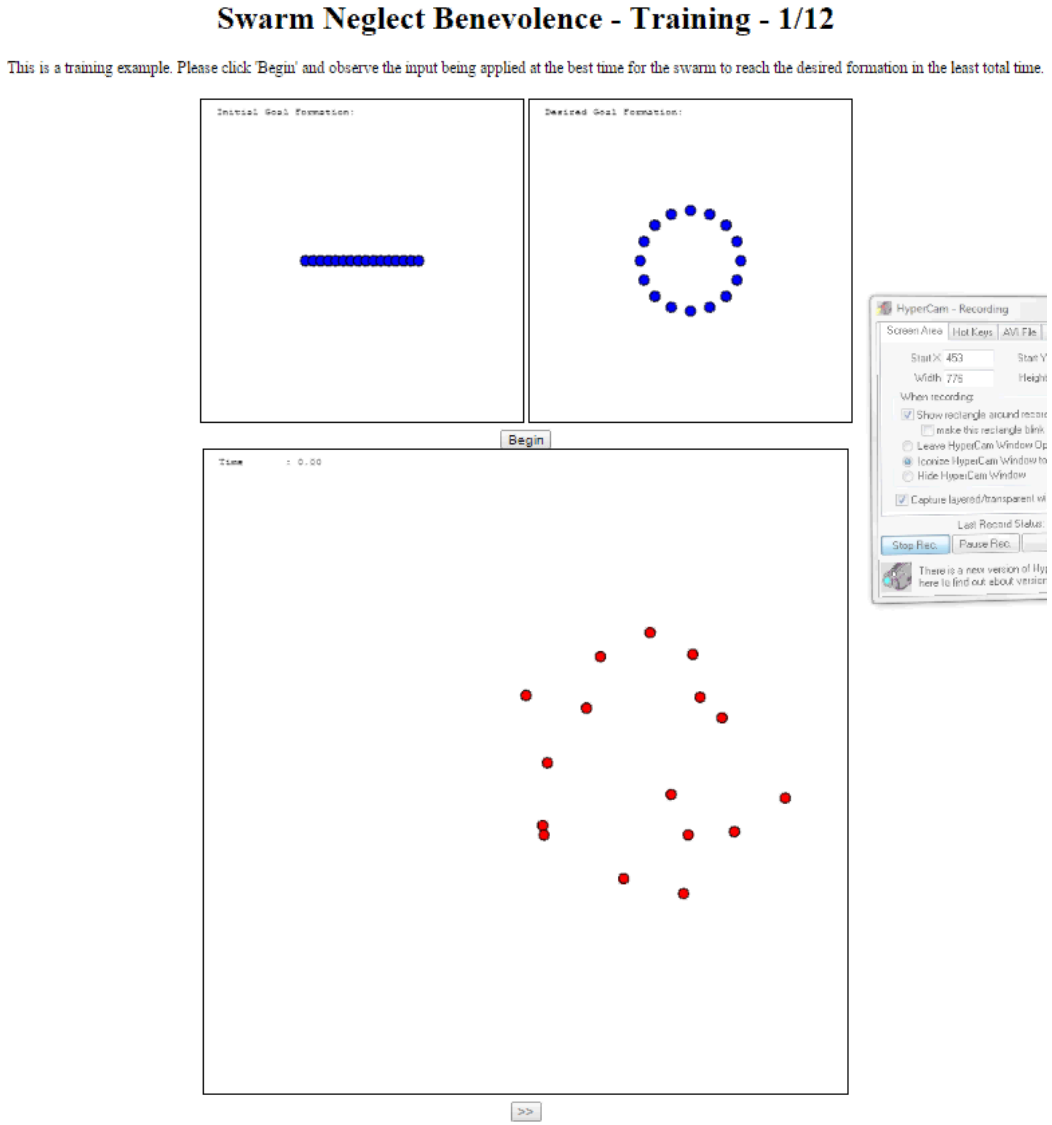
- Swarm is evolving towards its natural goal (original configuration)
- Operator desires a new goal (different configuration)
- Operator supplies input to divert swarm to new goal
- Can humans choose the optimal time?
- Human performance is compared with optimal performance (timing of input for NB task)

Intelligibility of Swarm Behavior

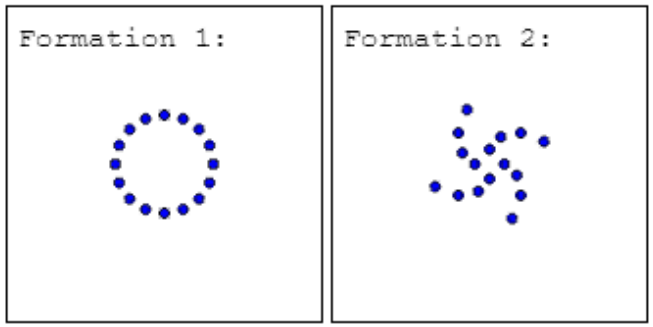
- Ability to recognize swarm behaviors depends upon human perception of regularities (Gestalt principle of common fate) in interactions between swarm members
  - Heading, velocity, proximity, etc.

- Because swarm behavior such as switching between formations provides few of the Gestalt cues people use to recognize coherent behaviors
- Could we augment the display to help them recognize the closest point between trajectories?

Visualizing Swarm Behavior

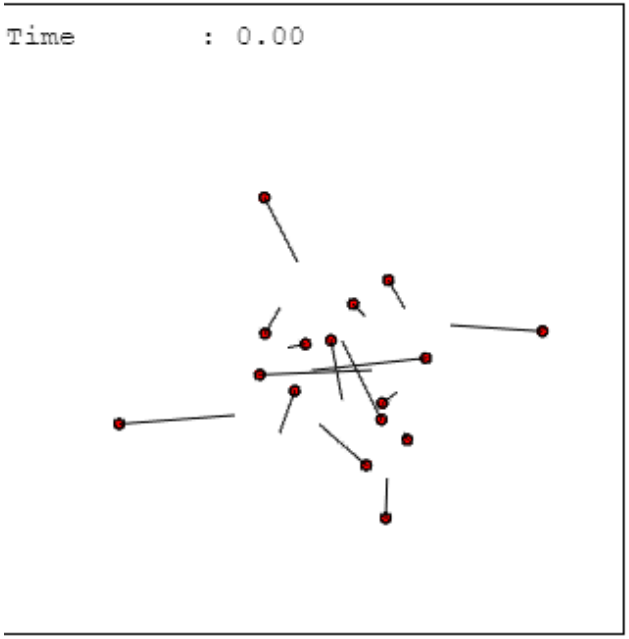


Visualizing Swarm Behavior

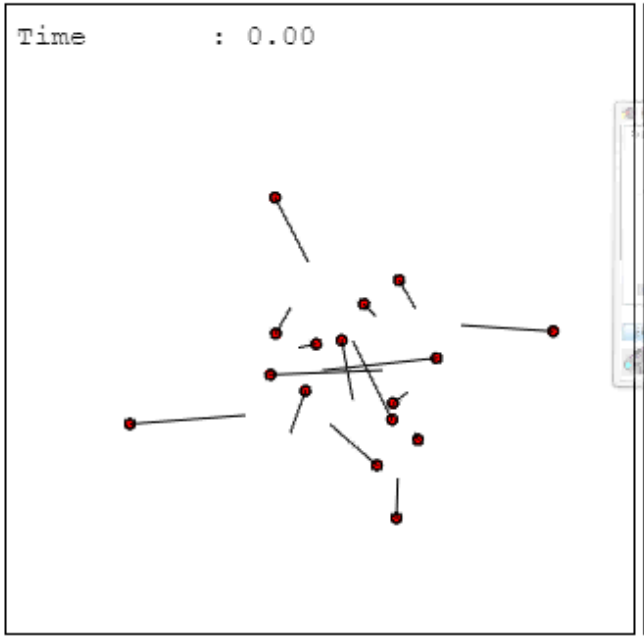


Begin >>

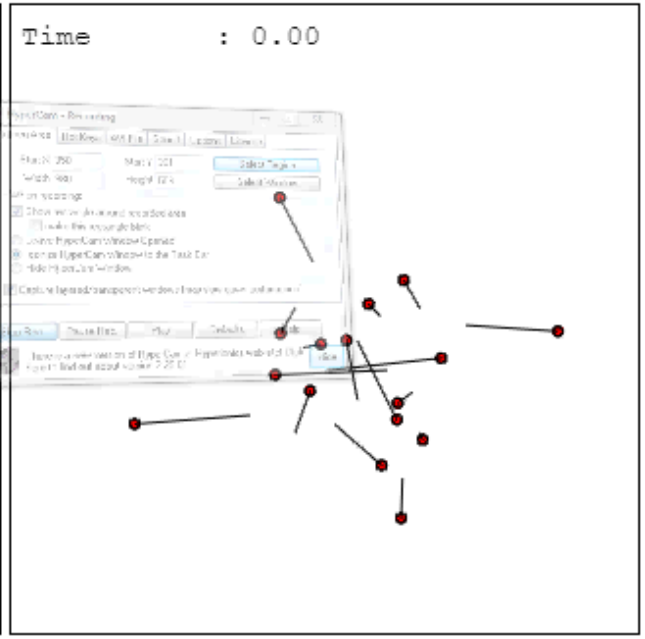
(1) Too Early



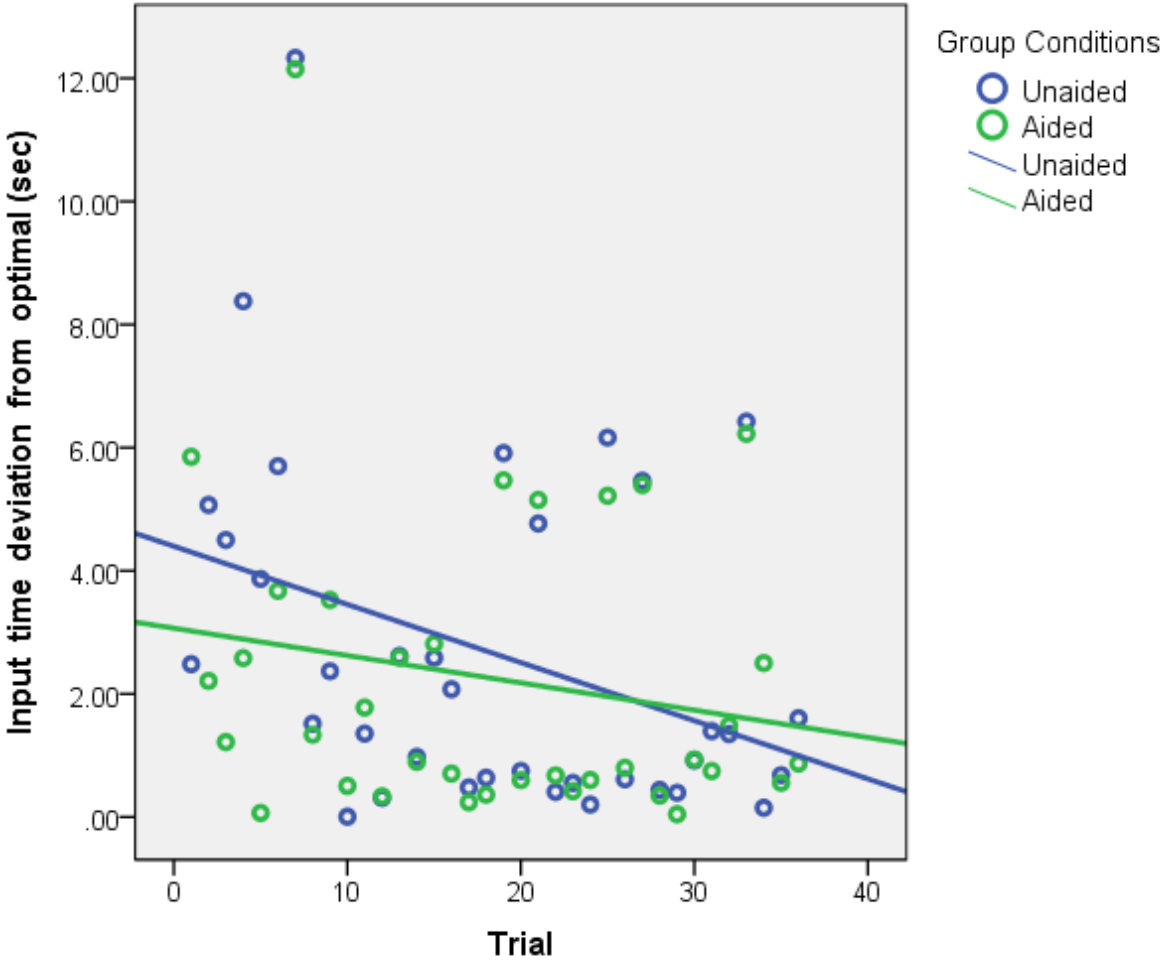
(2) Best Time



(3) Too Late



Deviation from Optimal



Nagavalli, S., Chien, S., Lewis, M., Chakraborty, N., & Sycara, K. (2015). Bounds of Neglect Benevolence in Input Timing for Human Interaction with Robotic Swarms. Proceedings of the 10th ACM/IEEE International Conference on Human-Robot Interaction (HRI 15).

Current and Future Work

- Quantitative model of human trust in swarm
- Communication of Human “trust signal” to swarm
- Swarm interpretation of “trust signal” (human intent)
- Swarm self-monitoring algorithms for performance degradation (e.g. monitoring for holes, for goal deviations due to need to avoid obstacles)
- Human intelligible display of swarm self monitoring results (human interpretation of swarm intent)
- Swarm repair algorithms
- Ways to convey human response to swarm self-monitoring (repair) results
- Human Interaction with single robots
  - Self-reflection
  - Adjustable autonomy

Recent Relevant Publications

- Luo, W., Khatib, S., Nagavalli, S. Chakraborty, N., Sycara, K., Distributed Knowledge Leader Selection for Multi-Robot Environmental Sampling Under Bandwidth Constraints, IEEE IROS 2016

- Li, A., Luo, W., Nagavalli, S., Chakraborty, N., Sycara, K. Handling State Uncertainty in Distributed Information Leader Selection for Robotic Swarms, IEEE SMC 2016, Budapest, Hungary, October 9-12, 2016

- Luo, W., Chakraborty, N., Sycara, K. Distributed Dynamic Priority Assignment and Motion Planning for Multiple Mobile Robots with Kinodynamic Constraints, American Control Conference, Boston, July 6-8, 2016.

- Walker, P., Lewis, M., Sycara, K. Characterizing Human Perception of Emergent Swarm Behaviors, IEEE SMC Budapest, Hungary, October 9-12, 2016

- Walker, P., Lewis, M., Sycara, K. The Effect of Display Type on Operator Prediction of Future Swarm States, IEEE SMC Budapest, Hungary, October 9-12, 2016Chien J-S., Lewis M, Sycara K., Liu, J-S., Kumru, A., Influence of cultural factors in dynamic trust in automation, Systems, Man and Cybernetics, Budapest, October 9-12, 2016.

- Chien, S-Y., Lewis, M., Sycara, K., Liu, J-S., Kumru, A. Relation between trust attitudes towards automation, Hofstede's cultural dimensions and big five personality traits, Human Factors and Ergonomics Society Conference, Washington DC, September 19-23, 2016.

- Chien, S-Y., Lewis, M., Hergeth, S., Semnani-Azad, Z., Sycara, K., Cross Country Validation of a Cultural Scale in Measuring Trust in Automation, Human Factors and Ergonomics Society, Los Angeles, October 26-50, 2015.

- Luo, W., Khatib, S., Nagavalli, S., Chakraborty, N., Sycara, K. Asynchronous Distributed Information Leader Selection in Robotic Swarms, Conference on Automation Science and Engineering (CASE), Gothenburg, Sweden, August 24-28, 2015.

Recent Relevant Publications

- **Mitchell, D., Chakraborty, N., Michael, N, Sycara, K. Multi-robot Persistent Coverage with Stochastic Task Costs", International Conference on Intelligent Robots and Systems (IROS), Hamburg, Germany, September 28-October 2, 2015.**

- **Walker, P. Amirpour S. Chakraborty, N., Lewis M., Sycara, K. Control of Swarms with Multiple Leader Agents, International Conference on Systems, Man and Cybernetics, San Diego CA, October 5-8, 2014.**

- **Luo, R., Chakraborty, N., Sycara, K. Supervisory Control for Cost-Effective Redistribution of Robotic Swarms, International Conference on Systems, Man and Cybernetics, San Diego CA, October 5-8, 2014. (*Finalist for Best Student Paper Award).***

- **Nagavalli S., Lybarger A., Luo, L., Chakraborty, N., Sycara, K. Aligning Coordinate Frames in Multi-Robot Systems with Relative Sensing Information, International Conference on Intelligent Robots and Systems (IROS), Chicago, September 14-18, 2014**

- **Walker, P., Amirpour S., Chakraborty, N., Lewis M., Sycara, K. Human Control of Robot Swarms with Dynamic Leaders, International Conference on Intelligent Robots and Systems (IROS), Chicago, September 14-18, 2014**

- **Chien, S.Y., Semnani-Azad, Z., Lewis, M. Sycara, K. Towards the development of an Inter-Cultural Scale to Measure Trust in Automation, 6th International Conference on Cross Cultural Design part of Human Computer Interaction International (HCII-2014), Crete, Greece, June 22-27, 2014 (*Best Paper Award*)**

- **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.**

- **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.**

Recent Relevant Publications

- Nunnally, S., Walker, P., Chakraborty, N., Lewis, M. Sycara, K Using Haptic Feedback in Human Robotic Swarm Interaction, HFES, , San Diego, September 30-October 4 2013

- Walker, P, Nunnally, S., Chakraborty, N., Lewis, M, Sycara, K. Levels of Automation for Human Influence of Robot Swarms, HFES, San Diego, September 30-October 4 2013. (*Best Paper Award*).

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- A. Kolling, S. Nunnally, M. Lewis, K. Sycara, "Towards Human Control of Robot Swarms", ACM/IEEE International Conference on Human-Robot Interaction, 2012.

- Chien, S., Mehrotra, S., Brooks, N., Sycara, K., & Lewis, M. Effects of Alarms on Control of Robot Teams, Proceedings of the 55th Annual Meeting Human Factors and Ergonomics Society (HFES'11)

- Dai, T, Sycara, K., Lewis, M. A game theoretic queuing approach to self-assessment in human-robot interaction systems. IEEE International Conference on Robotics and Automation (ICRA 2011), May 9-13, Shanghai, China, 2011.

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- Wang, H., Kolling, A., Abedin, S., Lee, P., Chien, S., Lewis, M., Brooks, N., Owens, S., Scerri, P. & Sycara, K. (2011) Scalable target detection for large robot teams, Proceedings of the 6th ACM/IEEE International Conference on Human-Robot Interaction.
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