Networked Human-Robot Swarms

Katia Sycara
Carnegie Mellon University
katia@cs.cmu.edu
• 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

Capabilities

Common Ground

Constraints

Task Requirements
Environment
Mental Workload
Affect
Learning

Behavior
Cognitive
Neuro

Mutual predictability
Trust
Synchronization

Behavior
 Algorithms
 Sensors/Effectors

Task Requirements
Environment
Hardware
Algo Scalability
Learning
Why human control of multi-robot systems?

Human Role

- Recognize & mitigate shortcomings of autonomy
- Utilize information inaccessible to autonomy
- Convey changes in intent and 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


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:

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

  – This is an upper bound, many practical limits
  – Our studies in search and rescue have shown this number to be 8
Typical MrCS interface
Can Operator Attention be Scheduled?

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

Attention direction via FIFO or alarms
- Monitoring $M$ could be eliminated

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

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
Select robot-to-repair sooner

Ordering:
1. Alarm
2. FIFO
3. Control

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

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

Shortest Job First (SJF) discipline yields maximum throughput

Experiment compared:
- SJF queue
- FIFO queue
- Alarm

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

2. **Tacit Leadership**
   Human influences swarm by controlling member(s) who then influence others but without any indication that influence originated with a “Leader”
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

Experiment Environment
Goals Reached

Flooding

- No Error: 15
- Error: 10

Consensus

- No Error: 5
- Error: 0
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 lose 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 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

Planar swarm of 10 robots. MVEE (turquoise), core set (gray), CH set (gray and green), internal (blue)
Knowing the states (positions) of the information leaders (robot 1, 3, 5, 7), instead of all 10 robots, will suffice to compute the ellipsoidal boundary for the entire swarm.

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

Early Input  Appropriate Input  Late Input
Illustration of Neglect Benevolence in State Space

System Dynamics - Natural

System Dynamics - With Human Input

- Natural Goal
- Human Goal
- Initial State
- Natural Path
- Possible Human Input Time 1
- Possible Human Input Time 2

State Variable 1

State Variable 2
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)
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?
Swarm Neglect Benevolence - Training - 1/12

This is a training example. Please click 'Begin' and observe the input being applied at the best time for the swarm to reach the desired formation in the least total time.
Visualizing Swarm Behavior

(1) Too Early

Time : 0.00

(2) Best Time

Time : 0.00

(3) Too Late

Time : 0.00
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


Recent Relevant Publications


Recent Relevant Publications


• 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)


Recent Relevant Publications


