Human-Swarm Interaction

a brief primer

Andreas Kolling
iRobot Corp.
Pasadena, CA
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?

Cognitive Complexity
Operator Resources

Number of Robots

Neglect Tolerance

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

O(n) Multi-Robot Call Center

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]

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

draw from research in mobile networks
draw from methods for gesture, speech and face engagement and specialized devices


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


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

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) …

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


III-A Cognitive Complexity

III-B Communication
   - State Estimation & Visualization
   - Control Methods

III-C State Estimation & Visualization

III-D Control Methods

III-E Levels of Autonomy

III-F Input Timing and Neglect Benevolence

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

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?
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 environments 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

![Bar chart showing mode usage]

- Stop**: 0.0
- Come***: 0.4
- Rendezvous: 0.2
- Deploy: 0.3
- Random***: 0.5
- Heading: 0.1
- Leave*: 0.0

* Selection
** Beacon
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

Swarm Controller

Connected to robot: 22

Robot Sensors:

0 2 0
0 0 0
0 18

Connection established
VBB: trial 1 has global visual feedback; 2,3 are blind
BBB: trials 1,2,3 are blind
Learned Neglect Benevolence

![Graph showing average initial inactive time (s) for different groups: BBB, VBB_V, VBB_B, Trained, Experts. The Experts group has the highest average time at 43.0 seconds.]
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