Evolving Robot Swarms and Groups

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Introduction

Introduction - General

Swarm Robotics: Field of robotics where a multitude of relatively simple physical robots operate in a coordinated manner

Key Concept: Focus is not on individual capabilities but on the collective behavior that emerges from the interactions among the robots and between the robots and the environment

Figure 1: *Colias - Low-cost Autonomous Robot that Replicates the Behavior of Swarming Honeybees [2]*

Introduction - Brief History

Origin: The concept is inspired by the social behavior of biological organisms (i.e, insects like ants and bees or birds) [3][4]

Flocks of Birds:
Detect motions spreading through the flock

Bee Swarms:
Collectively make decisions and adapt to new environments.

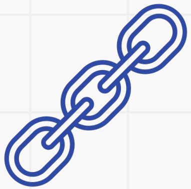
Ant Colonies:
Find the shortest path to resources through pheromone trails

Scientific Interest: Researchers observed these natural systems and theorized about applying similar principles to robotic systems

Introduction - Key Characteristics

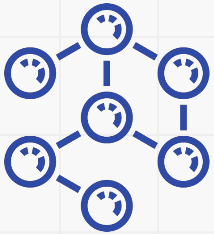
Group Size

Minimum number of individual entities must be three or more [5]



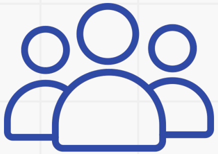
Robustness

Allows the robots to continue functioning despite individual failures or environmental changes [6]



Decentralization

Absence of a central control structure dictating the behavior of individual robots. So, no single point of failure [5]



Cooperation

Cooperation between robots based on a simple set of rules [5]

Introduction - Local Communication

- **Mechanism**: Individual robots communicate with one another within a local environment, rather than relying on a global communication system

- **Purpose**: Allows for propagation of information within the swarm (i.e., relay of information from one robot to another)

- **Benefit**: Supports redundancy and resilience; failure of a single robot does not significantly disrupt network of communication

Introduction - Components of a Swarm Robot

Anatomy: Physical structure, designed to be robust & modular with a power source (i.e., batteries)

Sensors: Getting signals/readings from environment or other robots to navigate, avoid obstacles, and position detection

Communication Device: Share information, increase coordination; crucial for swarm behavior

Actuators: Convert energy into movement; enable robot to move and manipulate objects

Onboard Communication: Interpret sensor data, decision making, and sends commands (actuators). Also stores software and algorithms that dictate the robot's behavior

Power Management: Ensures efficient use of the robot's power source for longevity and reliability

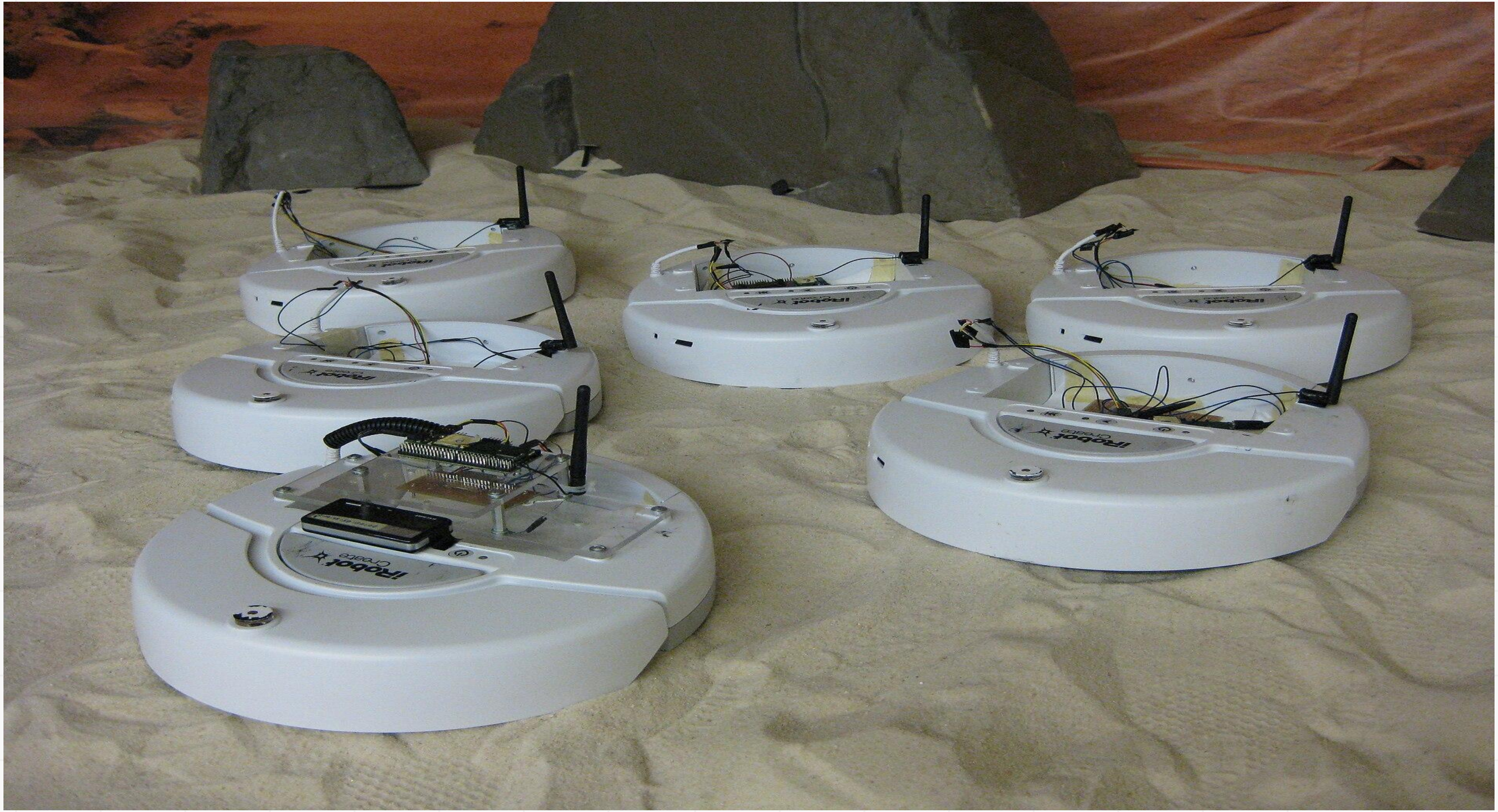


Figure 2: *A team of iRobot Create robots at the Georgia Institute of Technology [x]*

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Current Research

Current Research - Paper 1

Programmable Self-Assembly in a Thousand-Robot Swarm

- **Purpose**: System that demonstrates self-assembly of complex two-dimensional shapes with a thousand-robot swarm [7]
- Autonomous robots designed to operate in large groups and to cooperate via:
    - Local interactions - large-scale decentralized system
    - Highly robust collective algorithm for shape formation

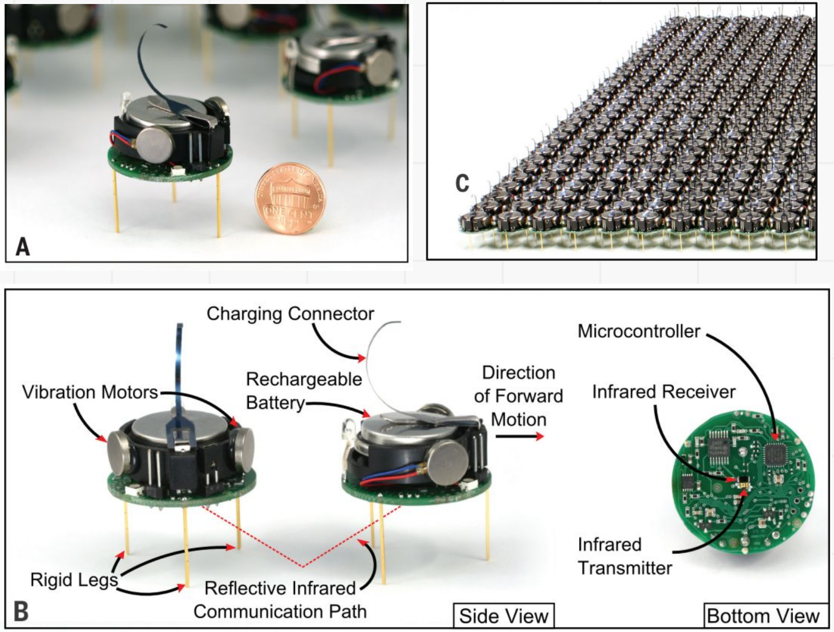

Figure 3: *Diagrams Describing the Swarm Robots (Kilobots) [7]*

Current Research – Paper 1

Programmable Self-Assembly in a Thousand-Robot Swarm

- Self-Assembly Algorithm composes of three primitive collective behaviors:
    - **Edge-Following**: a robot can move along the edge of a group by measuring distances from robots on the edge
    - **Gradient Formation**: source robot can generate a gradient value message that increments as it propagates through the swarm, giving each robot a geodesic distance from the source
    - **Localization**: robots can form a local coordinate system using communication with, and measured distances to, neighbors

Current Research - Paper 1

Programmable Self-Assembly in a Thousand-Robot Swarm

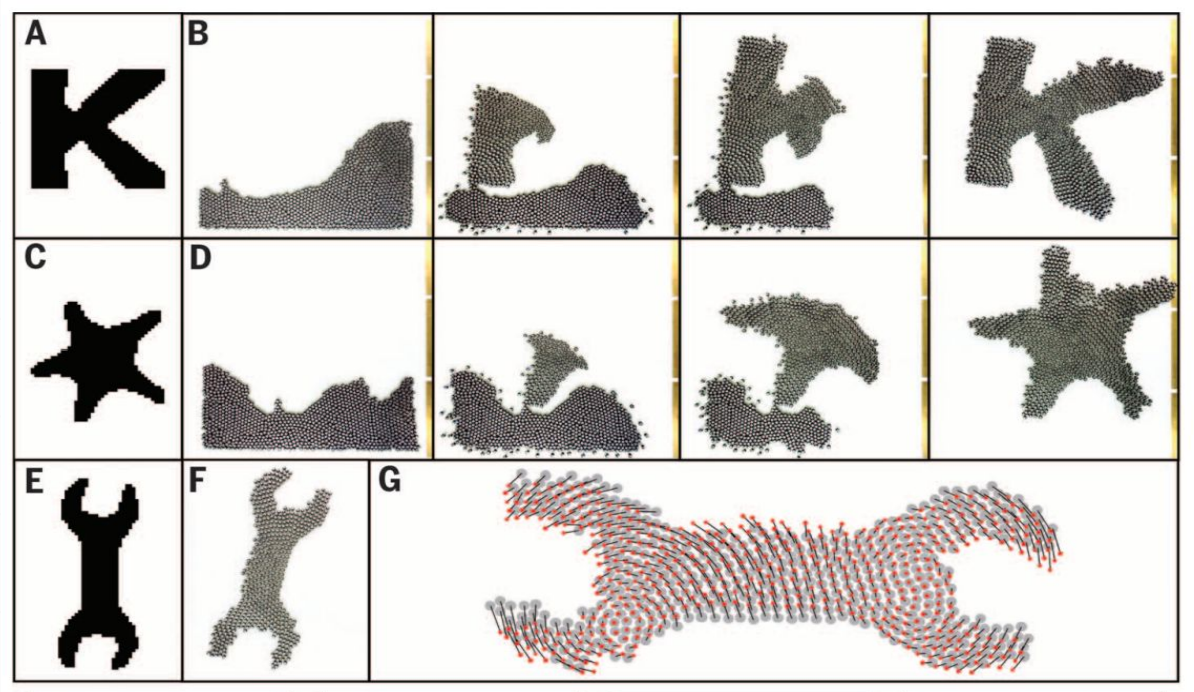

Figure 4: *Self-Assembly Process - Group of robots form the user-defined shape [7]*

Current Research - Paper 2

Swarm Robotic Behaviors and Current Applications

- **Purpose**: Collect and categorize basic swarm behaviors (algorithms) into spatial organization, navigation, decision making, and miscellaneous. [6]
- Apply to projects in industry where principal idea of swarm robotics is neglected
  - Swarm behavior via local interactions is hard to predict - proof of eligibility for applications can be difficult to provide
  - Current communication architectures may not match requirements for swarm communication - leads systems with centralized communication
  - Testing swarms is an issue - deployment in a productive environment can be risky and simulations may not be sufficiently accurate

Current Research - Examples

- Flocking of Birds:

Current Research - Examples

- **Ant colonies**:

03

Applications

Applications

Agricultural Tasks

Industrial Automation

Space Exploration

Search & Rescue Operations

Environmental Monitoring

Future Applications

- **Environmental Monitoring and Restoration:** Large-scale operations in oceans or forests for pollution control and wildlife protection
- **Space Exploration:** Using swarms to explore celestial bodies, conduct repairs, or build structures
- **Healthcare:** Micro or nano-robots for diagnosis, drug delivery, or surgical assistance

04

Simulation / Results

Simulation

Figure 5: *Recording of our attempt at Swarm Simulation in its Early Stages*

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Challenges

Challenges

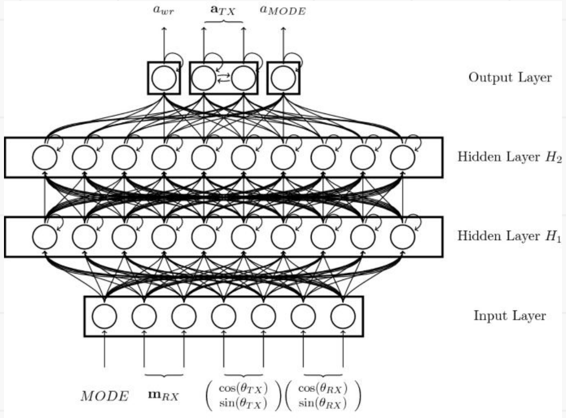
- **Complex Algorithms**: Designing algorithms that ensure efficient and effective communication and coordination among numerous robots is complex
- **Real-time Processing**: Necessity for real-time data processing and decision-making can be technically demanding
- **Scalability Issues**: Ensuring control system remain effective as the number of robots in the swarm increases
- **Energy and Resource Constraints**: Limited battery life, recharging infrastructure, and resource allocation

Swarm robots interact and coordinate locally to solve cooperative problems:

There are two main types of emergent communication:

- Abstract Communication: type of communication in which only the message content carries information, no environmental context message is processed.
- Situated Communication: scenarios in which both the message content and its corresponding environmental context carry information within the communication.

Continuous-Time Recurrent Neural Networks



- Continuous-Time Recurrent Neural Network (CTRNN) as the model to control the robot actions.
- CTRNNs are artificial neural networks with feedback connections that operate in continuous time.

Genetic Algorithm in Emergence of Communication

- A Genetic Algorithm (GA) is used to evolve the parameters of the CTRNN models that define the behavior of the agents.
- GA is a biologically inspired population based optimization algorithm that mimics how natural selection and survival of the fittest processes work in nature.

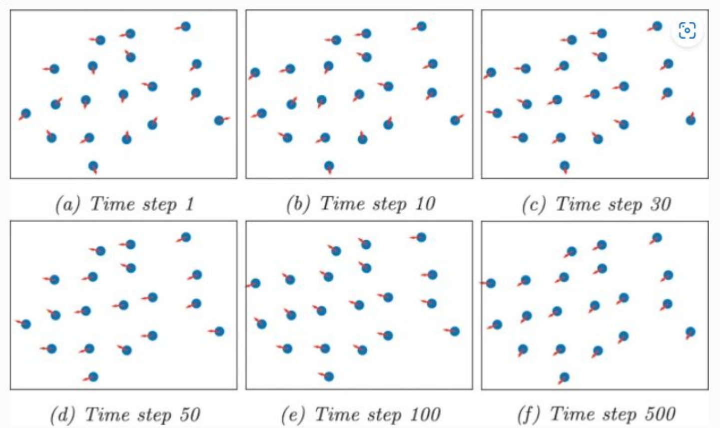


Figure 6: *Frames of a simulation of the orientation consensus experiment. Blue dots depict the robots in the swarm and red arrows show the orientations of the agents.*

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Conclusion

Conclusion

- Research, simulations, and the discussion of swarm applications provide a way to transform swarm robotics solutions from theory to real applications

- Variety of future applications where swarm robotics can prove to be useful

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No Questions?

Thank You!