COMP 4766
Introduction to Autonomous Robotics

Introduction to Swarm Robotics

By Andrew Vardy

April 4, 2014
Initial Definitions

What is a swarm? What is swarm intelligence (SI)?
What is a Swarm?

A swarm is a group of mobile agents (e.g. animals or robots; real or virtual) which exhibit the following properties:

1. There is no centralized control or synchronization between agents
2. The agents sense and communicate locally

Property 1 implies that no one agent is in charge. Agents can have special roles and they can influence each other, but no agent can make decisions for the whole group.

Property 2 implies that no agent has a complete picture of the environment.
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What is Swarm Intelligence?

Swarm intelligence (SI) refers to the ability of a swarm to solve a problem collectively.

Advantages of SI over other problem-solving methods:

- Robustness to failure or malfunction of individual agents and external disturbances
- Flexibility to tackle many similar problems
- Scalability to tackle large and small problems

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Examples of SI in Biology

We will look at some initial examples of SI in biology. This will motivate our discussion on the principles of SI.
Example of SI in Biology: Ant “Cemetery” Construction

Workers ants carry dead ants out of the nest and place them in clusters that merge and grow larger over time.
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LEFT: Computational model, RIGHT: Real ant behaviour

(Deneubourg et al., 1990)
Fig. 1. Clustering after 1, 100000 and 2000000 steps. 100 ALRs, 1500 objects, $k^2=0.1$, $k^3=0.3$, $m=50$, $e=0$, space=290x290 points. Small evenly spaced clusters rapidly form, and later merge into fewer larger clusters.

Fig. 2. Clustering in a colony of *Pheidole pallidula*. 4000 corpses were placed on a 50x50cm arena, and photos taken at time 0, 20 and 68 hrs. Small evenly spaced clusters rapidly form, and later merge into fewer larger clusters.

(Deneubourg et al., 1990)
Deneubourg et al’s Model

- Each agent applies a random walk and is able to measure the local density of objects

\[ p(\text{pick up}) = \left( \frac{k_1}{k_1 + \text{density}} \right)^2 \]

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- NetLogo demo
Example of SI in Biology: Honeybee Comb Structure

The typical pattern of honey (grey cells), pollen (white cells), and brood (black cells) as seen on a honeybee’s comb. Shown is the top-left corner of the comb.
Example of SI in Biology: Honeybee Comb Structure

There is a characteristic pattern of concentric brood, pollen, and nectar cells.

Fig. 2. The typical pattern of honey (grey cells), pollen (white cells), and brood (black cells) as seen on a honeybee’s comb. Shown is the top-left corner of the comb.
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There is a characteristic pattern of concentric brood, pollen, and nectar cells.

The problem being solved is to distribute the brood, pollen, and nectar to allow ready access to needed materials.
Agents: Queen, brood, workers.

Assumptions:

1. Queen lays eggs in a roughly random pattern in empty cells away near other brood cells.
2. Workers put pollen and nectar randomly in empty cells.
3. Workers obtain 4 times as much nectar as pollen.
4. Pollen consumed more quickly than nectar.
5. Pollen and nectar closest to brood cells consumed first.

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We will look next at self-organization (SO), a crucial property of SI systems.
Self-Organization (SO)

“Self-organization is a set of dynamical mechanisms whereby structures appear at the global level of a system from interactions among its lower-level components. The rules specifying the interactions among the system’s constituent units are executed on the basis of purely local information, without reference to the global pattern...” (Bonabeau et al., 1999):

We have seen ‘structures’ and ‘global patterns’ in both examples of SI shown so far.
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This definition is reminiscent of our overall definition for SI. However, SO is perhaps a broader concept that doesn’t specify anything about a problem being solved, merely that the local interactions among components creates some kind of global pattern.
Self-Organization can be observed in non-biological systems, for example in the formation of Bérnard convection cells (left) or regularly space ridges in dunes (right).
SO in Non-Biological Systems

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The difference in biological systems is that the interacting components in biology are typically much more complex than in non-biological systems (oil molecules, sand grains). Also, physical laws are in effect for both, but biological systems also adhere to behaviours that are learned and/or genetically programmed.
SO is supported by the following mechanisms:

- Positive feedback (amplification): Mechanisms that encourage certain quantities or patterns to grow. Recruitment of other members of the swarm to join in some activity is an example.
- Negative feedback (inhibition): Mechanisms that encourage certain quantities or patterns to shrink. Negative feedback can be explicit such as when one agent causes another to inhibit their behaviour, or it can be an implicit result of resource limits.
- Multiple interactions: The global structure or pattern arises over time through multiple interactions between components/agents.

We will see instances of these mechanisms in the following examples...
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- Perform a ‘waggle dance’ (see right) indicating the direction and distance of the nectar source which tends to recruit other bees to that source.
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- Continue to forage from her previous source without dancing.
- Abandon her previous source and follow another bee’s waggle dance, leading her to that source.
This schematic illustrates the choices \( (c_1 \text{ and } c_2) \) open to a bee returning to the hive from a food source.
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These choices are influenced by the perceived quality of the two food sources. Bees returning from high-quality food sources have a higher probability of dancing to support that source.
Performing the waggle dance to lead other bees to the same food source is an example of positive feedback that amplifies the selection of a large food source over a small one.
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In this experiment food source B is more plentiful in the morning (8:00-12:00) but food source A is more plentiful in the afternoon (12:00-16:00). Consequently, B attracts more bees in the morning and A attracts more in the afternoon.
Stigmergy is indirect communication between agents that occurs through the environment.
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Grassé developed his theory of stigmergy to explain the collective construction of termite mounds, which are massive complex, and take generations of termites to construct. He pictured the process like this...
FIGURE 1.13 Assume that the architecture reaches state $A$, which triggers response $R$ from worker $S$. $A$ is modified by the action of $S$ (for example, $S$ may drop a soil pellet), and transformed into a new stimulating configuration $A_1$, that may in turn trigger a new response $R_1$ from $S$ or any other worker $S_n$ and so forth. The successive responses $R_1$, $R_2$, $R_n$ may be produced by any worker carrying a soil pellet. Each worker creates new stimuli in response to existing stimulating configurations. These new stimuli then act on the same termite or any other worker in the colony. Such a process, where the only relevant interactions taking place among the agents are indirect, through the environment which is modified by the other agents, is also called *sematectonic* communication [329]. After Grassé [158]. Reprinted by permission © Masson.
An example of stigmergy that we have already seen is in the construction of cemetary clusters in ants.
An example of stigmergy that we have already seen is in the construction of cemetery clusters in ants. In Deneubourg et al.’s model for this behaviour, the ants react only to the local density of objects (i.e. dead ants), picking up isolated objects with high probability and depositing them with high probability when the density is high (in or near a cluster).
STIGMERGY:

Which of the following are examples of stigmergy (select all that apply)?

a. Leaving a mess in your apartment with the expectation that your roommate will notice it and clean it up.

b. Leaving a mess in your apartment and a message to your roommate that he should clean it up.

c. A bricklayer continuing an incomplete wall started by another worker.

d. A foreman giving verbal instructions to a roofer as to where the next shingle should be placed.

Select all of the above that apply.
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Select all of the above that apply.
HONEYBEE FORAGING:

Honeybees forage and return to the hive to perform or follow waggle dances. Is this an example of stigmergy?

a. Yes. The bees are communicating by modifying part of the environment.

b. No, because the bees are communicating directly.

c. No, because the waggle dance is not communication.

d. Yes. This is stigmergy because the only way insects communicate is through stigmergy.
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PLAY NOVA VIDEO
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Depositing pheromones in the environment is a classic example of stigmergy. The pheromones are not directed messages from one ant to another, but a modification of the environment that influences the behaviour of other ants. Let's look at ant foraging in a little more detail to understand this.
Example: Ant Foraging

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  - Generally ants find the shortest path between food sources and the nest
This is an example of positive feedback! The shorter branch has more pheromone deposited and therefore attracts the new ant. The new ant will also deposit more pheromone, amplifying the shorter branch even more!
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NETLOGO DEMO
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![Graph showing percentage of passages per unit time on each branch as a function of time.](image)

**FIGURE 2.1** Percentage of all passages per unit time on each of the two branches as a function of time: one of the branches is eventually used most of the time. Note that the winning branch was not favored by the initial fluctuations, which indicates that these fluctuations were not strong enough to promote exploitation of the other branch. The inset is a schematic representation of the experimental setup. After Deneubourg et al. [87]. Reprinted by permission © Plenum Publishing.
Example: Termite Nest Construction

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- The “royal chamber”, an open area surrounding the queen (an immobile termite, many times larger than any other termite)
- Tunnels that connect various chambers of the mound
- Three different types of termite (a.k.a. castes) are involved: the queen, builders, trail-followers, and nursing termites. Except the queen, real termites can switch between these roles and others, but they are fixed in the model.
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- Cement pheremone emitted by newly placed pellets
The virtual termites in this model have the following behaviours:

- Builders come into the world carrying a pellet of material, looking for a place to put it. Very similar to the cemetery cluster ants, they have a probability of depositing their pellet that is proportional to the amount of cemetery pheremone sensed. But they also sense queen/trail pheromone and will only place their pellet if the level of these other pheromones is in a certain range.

- Once a builder places its pellet, it disappears and is replaced by a new builder. This models the notion of the builder now leaving the scene to obtain a new pellet of material.
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Nursing Termites

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The nursing termites are very much like the trail followers except that they just move back and forth, away from the queen, then towards her. This models delivering food to the queen and taking her larvae.
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Fig. 3. A royal chamber being constructed. Parameters: $f = 400, r = 0.5, \alpha = \frac{1}{3}, v = 0.1, p = 0.1, n = 300, m = 5, s = 0.0.$
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Fig. 3. A royal chamber being constructed. Parameters: $f = 400, r = 0.5, \alpha = \frac{1}{4}, v = 0.1, p = 0.1, n = 300, m = 5, s = 0.0$.

LEFT: The queen pheromone restricts placement only to a certain range of distances away from the queen (blob in centre).
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![Diagram](image)

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Fig. 4. A royal chamber being constructed under mildly windy conditions (wind emanates from the upper-left lattice edge). Parameters as Fig. 2, except: $s = 0.15$. 
The swarm works well when there are many other agents acting on the environment, creating new opportunities for placement.
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Fig. 5. A graph showing the amount of work done per termite versus the number of termites present in the simulation. Each error bar represents the standard error from the results of 10 replicates. Note the geometric scale on the abscissa. The sinusoidal shape is similar to that observed in real termites (Bruinsma, 1979).
The creation of tunnels is a combined (but uncoordinated) effort by the trail followers who establish the trail and the builders who surround it with material.
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Fig. 6. A covered walkway is constructed. Parameters as Fig. 2, save that a flow of trail termites has been introduced: $t = 10, c = 0.5$. At each time step, between zero and 10 builder termites enter the lattice, with probability 0.5 per termite. The tunnel’s interior is clear of obstructions, and the cross-section is quite regular.
Here is the result of combing the queen, nursing termites, and builders
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Fig. 10. An example of entrance formation. Parameters as Fig. 2, except $e = 300$ (300 nurse termites are added) (a) 50 time steps: several (medium tone) pheromone trails between a central queen and the lattice periphery have formed (shown from above). (b) 500 time steps: only two trails remain. (c) 500 time steps: A view from inside the dome. (d) 800 time steps: only one entrance remains.
Swarm Robotics

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In addition to the promise of solving practical problems, SR has been used to test and validate scientific theories about animal behaviour.
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- **Simplicity** The individual robots are often claimed to be simple, but simplicity is a relative term. Therefore, the individual robots used by researchers vary enormously in their sophistication.
- **Size** How many robots does it take to make a swarm? Some claim >100, but most experiments consist of just a few robots.
- **Homogeneity** The members of the swarm may all be of the same type (homogeneous) or many different types (heterogeneous).
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References

