COMP 4766/6912: Autonomous Robotics

Introduction to Swarm Robotics

By Andrew Vardy

July 31, 2017
Outline

1. Initial Definitions
2. Examples of SI in Biology
3. Self-Organization
4. Stigmergy
5. Swarm Robotics
Initial Definitions

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

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Let’s take a look at some examples of swarms...
A swarm of honeybees looking for a new nest
Leafcutter ants retrieving building materials
Termite mounds taller than a Computer Scientist!
Chains of robots showing the path from point A to B
Spontaneous lane formation in human crowds
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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.
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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
### Examples

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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
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Fig. 1. Clustering after 1, 100000 and 200000 steps. 100 ALBs, 1500 objects, $k^* = 0.1$, $k = 0.3$, $m = 50$, $e = 0$, 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

\[ p(\text{pick up}) = \left( \frac{1}{k_1 + \text{density}} \right)^2 \]

\[ p(\text{drop}) = \left( \frac{\text{density}}{k_2 + \text{density}} \right)^2 \]
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- Each agent applies a random walk and is able to measure the local density of objects.
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NetLogo demo
Example of SI in Biology: Honeybee Comb Structure

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.

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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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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Self-Organization (SO)

We will look next at self-organization (SO), a crucial property of SI systems.
“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.
SO in Non-Biological Systems

Self-Organization can be observed in non-biological systems, for example in the formation of Béarnard convection cells (left) or regularly space ridges in dunes (right).
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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.
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We will see instances of these mechanisms in the following examples...
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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.
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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).
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.

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

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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 cemetery 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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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.
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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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**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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1. Night entrance and exit;
2. Underground water supply for drinking and cooling nest;
3. "Lungs" that expel rising hot air;
4. Cool air eventually sinks back to the cellar;
5. Warm air rises via central air duct;
6. Interior oxygen diffuses through the chimneys.
In (Ladley and Bullock, 2005) some of the models proposed for termite mound construction are summarized.
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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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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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In constructing the royal chamber, only builder ants are required.
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Fig. 3. A royal chamber being constructed. Parameters: $f = 400, r = 0.5, \alpha = \frac{1}{7}, \nu = 0.1, p = 0.1, n = 300, m = 5, s = 0.0.$
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Fig. 3. A royal chamber being constructed. Parameters: $f = 400, r = 0.5, \alpha = \frac{1}{2}, v = 0.1, p = 0.1, n = 300, m = 5, s = 0.0$.  

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CENTRE: The clusters join and grow vertically.
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CENTRE: The clusters join and grow vertically.

RIGHT: A roof is eventually formed.

Fig. 3. A royal chamber being constructed. Parameters: $f = 400, r = 0.5, \alpha = \frac{1}{f}, \nu = 0.1, p = 0.1, n = 300, m = 5, s = 0.0$.
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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.
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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 (SR) is the application of the principles of swarm intelligence (SI) to 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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**Homogeneity** The members of the swarm may all be of the same type (homogeneous) or many different types (heterogeneous).
