Natural strategies for search

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Abstract   In recent years a considerable amount of natural computing research has been undertaken to exploit the analogy between, say, searching a given problem space for an optimal solution and the natural process of foraging for food. Such analogies have led to useful solutions in areas such as optimisation, prominent examples being ant colony systems and particle swarm optimisation. However, these solutions often rely on well defined fitness landscapes that are not always be available in more general search scenarios. This paper surveys a wide variety of behaviours observed within the natural world, and aims to highlight general cooperative group behaviours, search strategies and communication methods that might be useful within a wider computing context, beyond optimisation, where information from the fitness landscape may be sparse, but new search paradigms could be developed that capitalise on research into biological systems that have developed over millennia within the natural world.

Keywords   Natural computing · Search · Foraging

1 Introduction

The field of Natural Computing is increasingly being utilised by engineers and scientists wishing to optimise solutions to problems that are intractable using conventional processes or would otherwise require massive computing resources. Generally, an acceptable optimal solution is discovered in the following manner: an initial position is identified in the search space (typically at random), and its acceptability assessed through the application of a fitness function; a position change strategy, consistent with the paradigm in use, is then

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iteratively applied with the hope of improving the acceptability; the final solution is identified either through achieving an acceptable level of fitness or on the completion of a set amount of computation (either chronologically or in terms of the number of cycles executed). Examples of such approaches include *inter alia* evolutionary algorithms (Friedberg 1958), which further inspired techniques such as genetic algorithms (Holland 1962, 1975); evolutionary strategies (Rechenberg 1965); evolutionary programming (Fogel et al. 1964) and, more recently, genetic programming (Koza 1992); ant colony systems (Colorni et al. 1991), and particle swarm optimisation (Kennedy and Eberhart 1995).

Sometimes, however, the search landscape is very flat. That is, the information returned by the fitness function is of little use until the selected position is within a given distance of a local or global optimum. In such circumstances, the techniques associated with optimisation may not be viable since they typically rely on informative landscapes to guide the search. A synthetic example might be the well-known multimodal test function referred to as Shekel's Foxholes (as used by De Jong 1975 to evaluate early genetic algorithms), whilst an application example might be autonomous robots searching for avalanche victims (Sandia National Laboratories 2001). In the latter case, the goal is the same as optimisation—finding a position within the search space that satisfies some criterion—but the techniques typically employed to solve, say, numerical optimisation problems, are not helpful in this context; hence, the need to consider a wider range of techniques. In other cases, the target may not be static, or may be trying to avoid detection; for example, as in a wide area security patrolling system (Sandia National Laboratories 2001). In such cases, a random walk or a deterministic search pattern may prove to be ineffective or inefficient, hence, the need to consider alternative search strategies. Therefore, this paper considers search in a broader sense than just optimisation and, although many of the techniques may be applicable to optimisation problems, some are only of interest in the more general search problems where a paucity of information may exist, such as might be encountered by autonomous agents in a real-world scenario. Further, autonomous agents must also be able to communicate their findings to the group. In a perfect world this is a fairly simple requirement, but in harsh environments where, for example, the physical landscape or electromagnetic interference are problematic, the group of agents may require alternative techniques.

The aim of this work is look to nature and the search and communication strategies that have evolved over millennia to produce the effective predatory behaviour observable today, illustrating how some of this has inspired natural computing paradigms, and, hopefully, provide inspiration for new developments. This does not suppose that there is one strategy for all occasions, but, that where there is a priori knowledge regarding the type of targets expected to be encountered, nature may well have already developed an effective solution. Where a priori information is unavailable, then it may be useful to have an array of strategies that can be selected according to environmental information, either sensed by the computing agent or passed to it by a cooperating ally.

The remainder of this paper is structured as follows. Section 2 introduces types of cooperation and group behaviour. Section 3 provides an in-depth examination of various natural search behaviours. Common methods of communication to facilitate cooperation within a group are examined in Section 4. Section 5 briefly considers indicative foraging behaviour, to illustrate how some of the behaviours highlighted in the preceding sections combine to produce effective cooperative predation. Section 6 discusses the exploitation of these behaviours, providing examples of how some have been utilised to develop natural computing paradigms; some less well-known examples are deliberately selected, to highlight the breadth of research already taking place.

2 Natural cooperation and group behaviour

The manner in which non-human animals (hereafter, animals) cooperate has fascinated biologists for many years. Cooperation among individuals of the same or different species may at first seem contradictory to the evolutionary principle of the survival of the fittest. Stevens et al. (2005) argue that all forms of cooperation must benefit the cooperators, whether directly, for example in mutual grooming, or indirectly, where cooperation helps to ensure genetic survival (an example of this being the division of labour in eusocial insect colonies, where individuals forego breeding in order to provide some other function that benefits their siblings).

Dugatkin (1997) reviewed the four main, accepted, types of animal cooperation: reciprocity, where an individual performs an action with the expectation that the beneficiary will reciprocate (e.g. impala grooming); by-product mutualism, in which cooperation only occurs when it provides immediate benefits that outweigh possible benefits that could be accrued uncooperatively (e.g. lions hunting in packs); kinship based cooperation, where individuals cooperate for the benefit of their genetic relatives (e.g. ground squirrels alarm calling), and group selected cooperation where an individual works at personal cost, but for the benefit of the group (e.g. foraging ants). In addition to these main types, animals may also cooperate to avoid some form of punitive measure. For example, Hauser (1992) presented evidence that rhesus monkeys announce food capture to avoid attacks that occur when they withhold the information.

Exactly why animals congregate and operate as a group is debateable due to several inter-related factors such as protection from predation, environment and availability of food sources (Morrison et al. 1987). However, this work concentrates on the strategies and tactics that animals use to search (usually for food). First, it is useful to establish how individuals interact, and, especially whether the group consists of an aggregation of individuals, a group of individuals working together for mutual benefit, or a team of individuals each with their own specialised role.

Aggregations can occur where there is restricted access to a resource, and individuals are forced together, in such an example, neither the individual nor the group benefit from the grouping. Freeman and Grossman (1992) studied group foraging by stream minnows, and noted that group members at feeding sites were actually just an aggregation of individuals who arrived and departed individually or in small groups because that was where food was located. This type of behaviour does not accrue any added value and is therefore not considered further in this paper.

The defining attribute of group behaviour is that the individuals perform the same task concurrently. This is relatively easy to achieve and can be very effective. Anderson and Franks (2001) categorised two broad groups as either those that form physical structures (known as self-assemblages) such as bridges, bivouacs and rafts (Anderson et al. 2002), or those that combine to form a more effective force, for example, ponerine army ants (Maschwitz et al. 1989), that, upon encountering a suitable foraging location, overpower prey much larger than themselves through swarming.

Where animals work in teams, there is a requirement for a more structured approach than needed when working alone, since individuals or sub-groups have separate sub-tasks to perform, which must be coordinated to achieve the overall team goal. In this highly complex behaviour, the individuals may be working sequentially or concurrently. Anderson and Franks (2001) note that team members are not restricted to the performance of a single simple task; they can change their role to fulfil group needs, although performance can be degraded where an individual performs an unfamiliar task. Gordon (2003)

reviewed how work was organised in colonies of harvester ants, and indicated that, whilst there was no central coordination, each individual based its behaviour on its encounters with the environment and other colony ants, forming a form of ad hoc dynamical network. For example, to coordinate foraging, the following activity takes place: initially, a group referred to as patrollers (pro-active foragers) leaves the nest in search of food sources; on encountering a food source, the patrollers return to the nest; reactive foraging ants leave the nest and forage along the trails taken by the patrollers; as foraging continues, the patrolling ants maintain the trails by encounters with the foragers; once the foragers cease to meet patrollers the foraging stops and all ants return to the nest. It has also been shown that group foraging may not always be the optimum strategy due to the potential cost of information sharing. Dechaume-Moncharmont et al. (2006) developed mathematical models of insect foraging that indicated that there may be times where, instead of waiting at the nest for foraging information, reactive foragers would fare better if they left the nest and searched for food proactively. This argument is supported on the grounds that, where food availability is transient, the time taken to return to the nest can be more costly than the returns made through the cooperation.

Individuals that work both alone and in groups can also be seen to change their behaviour to optimise their current mode of operation. In studies of social monkeys, Boyer et al. (2004) observed that the trajectories of individuals altered to a more optimal Lévy search pattern when foraging in groups (from $\mu \approx 1.5$ in individual foraging to $\mu \approx 2.1$ in groups, see Section 4.3.1). This switch in pattern is believed to be due to the increase in resource information available to the group and is considered the most efficient strategy under those circumstances. It is important to note that, although foraging became more efficient with larger groups, it was resource availability that affected group size; fewer resources resulted in smaller groups although the group members would change throughout the day. It is useful to note that competition for the available resources does not always dictate the size of the group, members of a group can accrue other benefits such as mate availability. Delestrade (1999) conducted experiments using alpine choughs to ascertain the effect of competition and food availability on flocking behaviour. She found that where food sources were small in size and plentiful (competition was low) the alpine choughs did not require social interaction and the efficiency of belonging to the flock was high. When the food sources were large and patchily distributed, this efficiency was reduced because the number of birds visiting the site remained the same, but not all birds gained access to the food. In these experiments, where competition was high, the female members stayed with the group despite restricted access to food, which was dominated by the males. In this case, Delestrade concluded that it was the mating benefit that was more important. Thus, some caution must be applied when observing natural phenomena, such as group feeding, in search of new natural computing paradigms, since misleading associations could be easily made; in this case are the group members acting cooperatively to gain mutual benefit or do individuals gather in conspecific groups simply because of the availability of food?

3 Search strategies

The success of a species depends on many factors, including its ability to search effectively for resources, such as food and water, in a given environment. Pianka (1966) broadly defined search strategies into sit and wait (for ambush) and foraging widely (for active searchers). Butler (2005) reports that, in general, active foragers range widely, eating slower prey, and expend high levels of energy in the process; in contrast, sit-and-wait

foragers capture fewer prey (which are usually the active foragers) but expend less energy in doing so.

Differing species utilise a variety of search strategies depending on their physiological characteristics, the environment, and the resources available to them. These can range from a continuous motion search (also called cruise search), such the long-range foraging patrols of the albatross (Stahl and Sagar 2000), through saltatory search, such as tyrant flycatchers (Fitzpatrick 1980), to the ambush type predation of the scorpion (Skutelsky 1995). It is important, therefore, to understand the types of environment, in order to establish which type of search is appropriate. The following subsections briefly examine pertinent characteristics of search environments before considering the strategies employed in nature to address search tasks within them. O'Brien et al. (1990) provide a useful summary of search strategies and the appropriate circumstances under which they should be adopted.

3.1 Search environments

Resources can be distributed uniformly or regularly, and may vary temporally and spatially; where they are distinctly grouped they are termed patchy. Where distribution is regular and stable it is advantageous for the predator to be easily conditioned to the most effective strategy and then to maintain it. Papaj and Rausher (1983) describe two types of conditioning that may take place: conditioning of response, where behaviour is learned through repeated encounters with stimuli, and conditioning of perception, where probability of perception is increased through repeated encounters. The effect of this was shown in experimentation on butterflies (Wiess and Papaj 2003), where butterflies alighted more frequently on model flowers with colours that they had been conditioned to believe would be more profitable in terms of nectar foraging and ovipositioning. The work indicated that, whilst efficiency improved in same context activity, it led to mistakes occurring following both behaviour switches (between foraging and ovipositioning) and environmental context switching.

For patchy or irregular resources, a predator will avoid becoming conditioned because to do so would leave it too dependent on a particular, possibly unreliable resource. Burns (2005) illustrates how this can occur in conspecific group foraging (in this case, with bees) where he argues that it can be beneficial for a group when individuals within it display different foraging behaviours to exploit the variable resources available, *i.e.* the group itself does not become conditioned.

3.2 Sit-and-wait

There are times when active searching does not provide sufficient energy gains to warrant the effort required; for example, in a harsh environment, or where prey speed or agility make it highly unlikely that the predator would capture the prey in an open pursuit. Naturally, in a predator/prey situation, the predator must be sufficiently camouflaged to avoid being detected until the prey is close enough to attempt capture.

As with most natural search strategies the tactic is often used in conjunction with other tactics to provide maximal benefit, such as in the case of the sidewinder snake (Secor 1994). In this study, sidewinders often performed either a straight line or random walk search, both in combination with chemoreception, to locate a suitable ambush site at the entrance to a prey burrow. Once located the Sidewinder would partially bury itself in the sand to provide camouflage, environmental protection and an anchorage from which an attack could be launched.

3.3 Continuous motion search

Bell ([1991](#)) offers four theoretical continuous motion search strategies: random walking, where the direction of each step is changing at random; straight line walking in a random direction for some distance; systematic strategies, such as spiral patterns, and kinesthetic input mappings. The latter case, in which the animal uses knowledge of its own previous movements to search for a return location such as a burrow, is part of a navigation system known as path integration or dead reckoning, which may include idiothetic (internal cues) or allothetic (external cues) mechanisms (Merkle et al. [2006](#)). Animals may use a combination of these in a variable strategy determined by individual needs, group needs or environmental factors.

After examining several experiments designed to assess the affect of spatial distribution on search patterns, Bell concludes that the dispersal of resources affects the locomotory search pattern in that the search patterns of those insects under examination was sufficiently plastic to be constrained by the resource dispersion rather than inherent patterns.

The following subsections elaborate further on each of the continuous motion search tactics.

3.3.1 Random walk

A random walk may consist of either Brownian motion, where the direction of one step is independent of its predecessor, or Lévy paths, where there is a lower probability of a change in direction. For hidden fixed targets, Lévy paths have been utilised by several species when foraging for food. Examples of such behaviour have been observed in spider monkeys (Ramos-Fernández et al. [2004](#)) and jackals (Atkinson et al. [2002](#)), amongst others. Lévy path lengths (l_j) can be described as being stochastic with continuous probability (P) having stationary and independent movement increments with distribution:

$$P(l_j) = l_j^{-\mu} \qquad (\text{where } \mu \approx 2) \tag{1}$$

Viswanathan et al. ([1999](#)) showed that Lévy search is a statistical random search that outperforms normal random search (i.e. Brownian motion, where $\mu \geq 3$) under certain searcher/resource conditions, particularly where prey density is low. This may appear to be counter-intuitive since Brownian motion paths produce more homogenous coverage and would be more likely to find widely dispersed targets. However, when the general overriding principle for foragers is that of maximising efficiency, where sufficient food is available, then more intense, systematic, local search would require less effort (see Fig. [1](#)). Viswanathan et al. ([2001](#)) investigated the efficiency of the approach under such circumstances. They defined the search efficiency function $\eta(\mu)$ as the ratio of target sites visited to total distance travelled:

$$\eta = [N\langle l \rangle]^{-1} \tag{2}$$

where N is the mean number of Lévy flights between successive target sites, which was computed (Marthaler et al. [2004](#)) as:

$$N \approx (\lambda/r_v)^{\mu-1} \text{ (for destructive searching)} \tag{3}$$

$$N \approx (\lambda/r_v)^{\frac{\mu-1}{2}} \qquad \text{(for non-destructive searching)} \tag{4}$$

for $1 < \mu \geq 3$, and assuming λ (the mean distance between targets) is the fixed maximum step size and r_v (the vision distance) is the minimum step size. For destructive searching
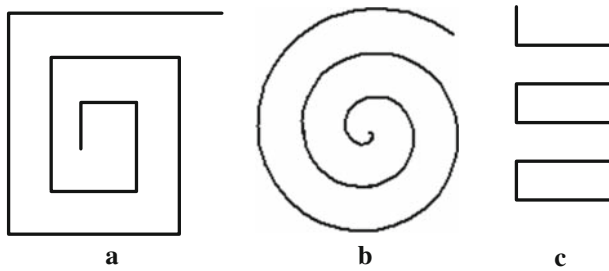
Fig. 1 Hypothetical systematic search strategies; (**a**) expanding square, (**b**) spiral and (**c**) parallel sweep (Bell (1991), Fig. 6.1)

(i.e. where prey numbers are finite and consumption noticeably reduces abundance), the optimal efficiency of the search was found to occur when μ is as close to 1 as possible, and for non-destructive searches, as a function of λ and r_v:

$$2 - \delta(\lambda, r_v) \tag{5}$$

where $\delta \approx 1/[\ln(\lambda/r_v)]^2$.

Further comparisons between Lévy and Brownian motion searches in a biological context were made by Viswanathan et al. (2002) and Bartumeus et al. (2002), to assess predator success against varying prey densities and motion types. The relationships among these factors are complex, but for a given target density, they indicated that, for Brownian motion targets, predators that are larger and faster are better served by Lévy search, whilst for smaller and slower predators, Brownian search was a better option. Where targets moved using Lévy motion, size ratio was unimportant and velocity ratios dominated, with Levy searching being preferred for slower targets. Target density was regarded as the prime factor, with Lévy search only being suited to lower density targets, although a target with Lévy motion reduced this effectiveness. Further, where targets have a proportionally higher velocity or super-diffusive movement, Lévy search is less profitable; indeed Brownian search or even no search at all (sit-and-wait) is usually adopted since the prey is just as likely to move into sensory range without the higher effort required for Lévy search.

3.3.2 Straight-line search

A strategy that includes straight line searching can be effective when there is no other information regarding resource location and provided the searcher does not pursue the same line for an inappropriate length of time. If the time period between direction changes were too short, the search area would be too constrained; if it were too long, the searcher may unnecessarily follow an unproductive path. It can also be shown that the strategy is inefficient when the resource density and sensory acuity are small, since the probability of target detection (T_d) is:

$$T_d = \frac{\arcsin(\alpha/r_0)}{180} \tag{6}$$

where α is the detection radius and r_0 is the distance between the start point and target. Using several case studies, Bell (1991) indicates that when the searcher does decide to

move it usually uses a strategy, such as alternating left and right turns (with a mean angle of 35°), that reduces the possibility of revisiting previously searched territory. Further, this strategy may be useful in group search scenarios since the decreased turning rate may make the search more efficient than strategies with higher turn rates, since the likelihood of each predator covering the same ground as another predator is also decreased.

3.3.3 Systematic searches

Bell ([1991](#)) discusses three hypothetical systematic search tactics. The expanding square, the spiral and parallel sweeps (Fig. [1](#)). To be most effective the search path should be spaced at twice the sensory acuity of the searcher. These strategies are most viable where the target is moving slower than the searcher and there is no spatial or temporal information.

Whilst there is a paucity of evidence for such tactics in the literature, Müller and Wehner ([1994](#)) indicate that desert ants use spiral searching as part of a homing strategy that includes Path Integration (PI). In this case the ants use the PI strategy to calculate a global return vector, which is used to return to the nest after a foraging sortie. The return vector is not always sufficiently accurate, and when they do miss the nest they enter an expanding spiral search.

3.3.4 Path integration

An animal will often need to search for a location that it has moved away from, for example, a previously lucrative location or its burrow. Possible tactics could be to employ one of the search patterns discussed, or to navigate using remembered landmarks, but these can be inefficient or error prone (a landmark might move, for example). Alternatively, the animal can map its outbound movements using idiothetic and allothetic mechanisms, and calculate a global return vector by an innate path integration (PI) ability (see Etiene and Jeffery [2004](#) and Merkle et al. [2006](#) for reviews). Two PI models have been proposed in both Cartesian and polar coordinate systems (only Cartesian models are shown here for comparison). Both models only require the animal to sense the input variables of forward speed (v) and angular turn rate (ω). The basic models are as follows.

Geocentric models are based upon the animal's perception of its movement in relation to its environment (allothetic inputs) where it continuously updates its global return vector through the integration of movements calculated using trigonometry. Research by Freake ([2001](#)) indicates that the parietal eye (a photo-sensitive organ present in some animal species) plays a significant role in the homing behaviour of the sleepy lizard suggesting that a form of celestial compass could be in use; this could be used to facilitate a geocentric PI system. In the geocentric PI model (Mittelstaedt [2000](#)) the global return vector $\mathbf{G}$ is:

$$\mathbf{G} = \mathbf{P}_0 - \mathbf{P} \tag{7}$$

where $\mathbf{P}_0$ is the origin [0,0] and

$$\mathbf{P} = \int (\cos\phi, \sin\phi)ds \tag{8}$$

if integration is over walked distance (s is the arc length), or

$$\mathbf{P} = \int (v\phi)(t)dt \tag{9}$$

if integration is over time, and

$$\phi = \int \omega dt \tag{10}$$

In contrast to geocentric models, egocentric models require less complex calculations, since the animal uses idiothetic input signals to calculate its forward speed and angular turn rate. Merkle et al. (2006) argue that although recent improvements to the geocentric model described above have included results consistent with mammalian neuro-activity, it has yet to be shown that animals have the ability to physiologically perform the necessary trigonometric calculations, the egocentric model is physiologically possible and simpler to calculate and therefore more plausible. For the egocentric model the update to the global return vector (X,Y) is:

$$\frac{dX}{dt} = -v + \omega Y \tag{11}$$

$$\frac{dY}{dt} = -\omega X \tag{12}$$

These geo- and ego-centric models need not be mutually exclusive; Menzel et al. (2000) argue that some honeybee navigation can utilise both systems. Generally, the argument is presented that honeybees only apply egocentric models since most evidence does not show that novel shortcut behaviour takes place when bees have been trained to fly a route to and from feeding sites. Findings from the experiments of Menzel et al., combined with supporting evidence from other work, suggests that they store relational information on landmarks and if they do not receive sufficient orientation to employ ego-centric based navigation they can use an alternative geo-centric system. This geo-centric system is believed to further use combinations of reference systems depending on the accuracy of available sources, such as scent deposits or visual cues for their 'odometer' (Vladusich et al. 2006).

Although these models present efficient mechanisms, they are not perfect, and a returning animal may not return to its start position. In this case another local search mechanism can be employed, such as a local random walk or a systematic search. As previously indicated, Müller and Wehner (1994) show this type of behaviour in desert ants, which perform a spiral search where PI fails to locate the return location of a foraging sortie.

3.3.5 Area concentrated search

Area concentrated search (ACS), also known as area restricted search, is a variable strategy in which a predator will attempt to exploit the natural tendency of prey to appear in patches, by concentrating their search effort in a particular area upon encountering an individual prey item. Searching often begins in a ranging mode, with long leg lengths and small turning angles, followed by intensive searching initiated by some kind of cue. This strategy can be termed *win-slow:fail-fast* since, when a successful encounter occurs the predator slows into intensive search, but speeds into extensive search when an encounter fails (Krakauer and Rodríguez-Gironés 1995).

An example of this behaviour is that of the juvenile plaice (Hill et al. 2000), which use localised cues, although it is not known what sensory apparatus is used, to alter their search pattern from extensive to intensive search. This switch, on average, shortened pause time by 15%, increased move duration by 14%, reduced speed by 22% and increased median

absolute turn angle by 33%. The effect of this change is that the predator can effectively search a small area very rapidly since it knows that once it has discovered one item of prey, it is likely to discover others nearby.

Krakauer and Rodríguez-Gironés (1995) presented an ACS model to examine several foraging rules:

- *Tracking errors*. These occur when the forager searches extensively where resources are good or intensively where resources are poor. With ACS it is possible to reduce tracking error by capitalising on patchy distributions through initiating intensive searching only on encountering prey items. The amount and types of error will therefore depend on the patchiness of the resource.
- *Learning*. The forager is required to learn about the environment and distribution of the resources to maximise exploitation. This activity must be balanced with the time available for, and value to be gained from, exploitation.
- *Evaluation of information*. The forager must decide whether there is any value in the information it gathers or to apply a general strategy instead. As the patchiness increases so does the likelihood of prior assumptions being incorrect and the value of time spent in assessing the prey distribution and selecting an appropriate exploitation strategy increases.
- *Functional response*. The prey intake in response to its density. The selection of a resource dependent strategy can alter the response curve from one in which, at high prey density, the limiting factor is the amount of time spent handling the prey, to one in which the predator chooses to spend more time searching.

Further to these rules, Krakauer and Rodríguez-Gironés also assessed whether the standard win-slow:fail-fast ACS strategy was always optimal. They argued that, where the resource distribution regularly alternates between good and bad, the reverse could be true (win-fast:fail-slow), since the switch to intensive mode is only worthwhile where the chances of successive encounters are high.

3.4 Saltatory search

Animals do not always need to have located prey to enter an intensive search phase; the intermittent scan and relocate foraging method, also known as saltatory search, is a widely adopted strategy when the targets are sparse and difficult to detect (Benichou et al. 2005). The strategy consists of two distinct phases, a search phase, in which the searcher pauses to explore its immediate vicinity (within the scope of its sensory acuity), and a motion phase, in which the searcher moves more quickly, such that it is not normally possible to detect hidden prey.

During the search phase, the predator may have to scan a given area many times in order to detect a well hidden target. Benichou et al. modelled the phase using a diffusion process (a random walk) that was notable in that it was a sensory search rather than the animal's physical movement. Results of the modelling closely matched that of several animal species, indicating that the diffusive search was an appropriate selection for the search phase.

The motion phase is notable in its similarity to the klinokinetic strategy used by the juvenile plaice (Hill et al. 2000) when changing from intensive to extensive searching during an ACS, although Benichou et al. (2005) adopted an efficient relocation strategy that had been observed in nature; a straight ballistic motion to the next search area. The

results of the modelling indicated that the optimal relationship between the average duration of the search and motion phases was bimodal (motion phase duration equals search phase duration to the power 3/5 or 2/3).

The similarity of this strategy with ACS is striking, but the difference is vital to the potential exploitation of either in a natural computing context. To summarise, ACS is suitable where predator acuity and prey visibility are such that a prey item can be detected during extensive search, whilst saltatory search is suitable where sensory acuity is limited or prey visibility is low, and is thus unlikely to be detected during extensive search.

3.5 Knowing when to give up

Once a predator has assumed a particular search tactic, it must then decide when to switch to another or move location, which is known as the giving up time (GUT). The decision could be based on factors such as estimated prey numbers, capture rate, or time (Bell 1991). For example, juvenile plaice (Hill et al. 2000) use a short-term klinokinetic strategy; that is, they will only exploit a patch for a short time before swimming away (by reducing their turn rate). This, it was argued, is because other external pressures are operating; if they loiter to fully exploit the patch, there is an increased possibility of predation. Charnov (1976) presented a more generalised departure strategy known as the Marginal Value Theorem (MVT). This states that, where an omniscient predator depresses prey availability, departure from a patch should occur when the capture rate drops to the average capture rate for the habitat.

A GUT also needs to be optimised for sit-and-wait predators since, in common with continuous motion predators, sit-and-wait predators often do not know prey density within a patch, and, furthermore, prey size may not be known until capture, and to give up before any capture is a waste of the expended energy (Iwasa et al. 1981). Nishimura (1999) explored, using modelling, the behavioural variability of GUT in a stochastic environment for sit-and-wait predators and indicated that, when entering an unknown patch, the predator should employ a variety of strategies to learn the optimal GUT. Nishimura asserts that the number of decisions made in search of the optimal GUT strategy would relate to the uncertainty of the environment and from this it is possible to further assert that to be optimal in highly stochastic environments, a predator should have an array of potential strategies to explore, and the efficacy of decision making in the pursuit of the optimum is vital.

3.6 Capitalising on environmental cues

A priori information regarding certain search target attributes can provide additional cues that can be used to improve the likelihood of success. These cues might be topographical or other environmental factors. For example, harbour seals have been shown to exploit their knowledge that salmon migration runs occur under certain tidal conditions and that during these runs the salmon densities are increased in constricted channel areas (Zamon 2001).

Environmental cues can also be used to avoid intra-specific competition. This is illustrated by the foraging behaviour of *Frugivorous lepidopteran* larvae (Marchand and McNeil 2004). These larvae feed on cranberry fruits and exhibit plastic foraging behaviours that are cued on fruit size, spacing and colour. The first two are self-explanatory: the larvae will exploit a patch where the resource can provide sufficient return on foraging effort, i.e. select the largest fruit in the densest patches. The fruit colour is significant since the larvae feed from the inside of the fruit to avoid predation and the activity of feeding larvae affect the fruit by turning them prematurely red. Other foraging larvae use this cue

to avoid wasting energy and possible intra-specific confrontation. The colour cue is so important that during laboratory controlled experiments, far higher numbers of larvae entered small green fruits than large red ones (even though the larger fruits offered potentially higher gains).

3.7 Variable strategies and patterns

The reasons for variations in search behaviour are diverse, but usually related to a changing environment or physiological state.

There are a variety of reasons why a variable foraging strategy can be optimal; for example, Skutelsky (1995) researched the scorpion *Buthus occitanus isrealis* and discovered that the subject had added active foraging to its usual sit-and-wait strategy, to maximise its predation of termites. The reason for this adaptation is that when a group of termites detects a predator they all retreat to the safety of the nest. Within seconds, by changing to an intensive search mode, the scorpion was observed to kill up to eight termites compared to the single kill that would be possible with a pure sit-and-wait strategy. This discontinuous variation is an example of an Evolutionarily Stable Strategy (ESS) as proposed by Maynard Smith (1982). Whilst the scorpions used prey-defined variation, female red-faced warblers vary their strategy due to breeding restrictions (Dobbs and Martin 1998). The warblers were observed capturing stationary prey from a perch (sit-and-wait) whilst egg laying or incubating, and hover-sallying for stationary prey during the nestling period. This variation was believed to be a result of changes in time and energy requirements since the former strategy occurred whilst the female nested alone and the latter was during a period when the male assisted with the hatchlings.

It is not just the foraging strategy that can be adapted; the search pattern itself can change in response to dynamic changes to the environment, although this requires that an individual acquires information about the environment and the optimality of its current strategy, and then makes a decision about the proposed pattern's efficacy. In stable, homogenous environments, this is a fairly straightforward decision, but real world situations are rarely simple and the learning/decision making process itself requires energy, and the individual must also decide, therefore, whether a net energy gain would result.

3.8 Repeat searches

In dynamic environments it can be important that an area is revisited to search for new resource occurrences. Bell (1991) describes several strategies:

- *Cropping*. Cropping is the process of depleting a resource, moving on, and then delaying a return until the resource has had time to renew. When implementing cropping, it is argued that a systematic approach is most efficient since resource renewal increases exponentially over time (notwithstanding unrelated environmental pressures).
- *Traplining*. This is similar to cropping in that it involves returning to the locations of previously successful encounters. In traplining, however, the searcher learns a successful foraging route that allows resources to recoup between foraging visits.
- *Partial depletion*. The predator can choose to only partially deplete the resource during a foraging visit, leaving resources available for return visits. This has the added advantage that the resource will replenish more rapidly due the exponential nature of resource rejuvenation.

All three share a common principle: that the resource is allowed to renew between visits. Whether they are employed very much depends on the goal of the target application.

3.9 Competitor avoidance

It is not beneficial for individuals to compete for the same resources. An example of this is searching for insect oviposition site selection; when the eggs hatch there should be sufficient local food for early larval survival. When searching for a site, the insect will examine the amount of resources available and maximise them by avoiding superparatism where other, better, resources are available. Cope and Fox (2003) conducted experiments that indicated that the seed beetle uses a combination of resource size, competition (i.e. existing eggs) and their own need to egg lay (older beetles were more likely to lay since it is better to lay sub-optimally than not to lay at all).

This principle can be applied to improve group searching, since the competitors for resources can be considered to be cooperating in the goal of ensuring the survival of the species. Thus, if a group of robots are searching for hidden resources, it is not efficient for them to cover the same ground (assuming a static environment) or to converge on small incidences of the resource.

4 Communication strategies

The manner in which inter-group communication occurs not only affects the efficiency of information passing but can also produce emergent behaviours in its own right. Communication strategies are often multimodal and can be either direct, where two or more individuals pass information and receipt occurs within the same time-frame as transmission, or indirect, which is usually more subtle, and occurs where a message is left, and any group member can receive it at a later time.

4.1 Indirect communication

Grassé (1959) first documented the method by which social insects communicate indirectly to achieve the complex emergent behaviour required to perform feats such as termite nest construction. He termed the process stigmergy (from the Greek *stigma*, goad, and *ergon*, work). To achieve stigmergy, multiple individuals interact when one modifies the environment and the others react in some way on encountering the modification. Essentially this description highlights the voluntary nature of response, for example, in the case of ants a receiver may choose to ignore a pheromone signal because the intended action is outside the responsibility of its caste (e.g. a soldier ant may well ignore food trail signals). Holland and Melhuish (1999) expanded on Grassé's concept of stigmergy occurring where activity is stimulated through changing the environment. They argued that it is the outcome of the behaviour that is important and can be manifest in three ways:

- It may affect an agent's choice of action.
- It may not affect the agent's choice of action but how it performs that action.
- It may affect neither of the previous points but influence the outcome. For example, by placing a physical barrier to alter the path of fellow group members.

In social insects the stigmergic reaction usually involves the application of low-level rules; in the termite nest-building scenario, a termite drops a piece of chewed earth when

encountering a raised piece of ground (generated by other termites dropping pieces of chewed earth) until large, complex structures emerge. Stigmergy is most commonly associated with ants and termites but is also used by other insects such as bees (Dornhaus and Chittka 2004) and wasps (Reed and Landolt 2000 and Steinmetz et al. 2003). Stale data is often avoided via mechanisms such as evaporation, where the importance of response time can be tied to evaporation rate.

4.2 Direct communication

The obvious forms of direct communication in social groups are through aural and visual cues, although direct communication can occur using all sensory cues, including the use of pheromones. The methods discussed in this section are not exhaustive; however, they do cover some of the direct communication methods that have already been used in natural computing. Also notable is that the latter two strategies (tandem calling and information centres) can be regarded as higher level strategies that make use of lower level forms of communication.

4.2.1 Trophallaxis

Some species of social insects communicate successful foraging information via the transfer of bodily fluids; this may be proctodeal (faeces sampling), or stomodeal (regurgitation). Dejean et al. (2005) report on research that indicates that trophallaxis is employed by tramp ants (and even simulated trophallaxis in less phylogenetically advanced sub-families) to pass information regarding good foraging sites located in the territory of interspecific competitors. In this instance, the odour of the competing group is contained within the transferred fluid alerting the receiver and therefore expediting exploitation of the site in order to avoid confrontation and thus gain competitive advantage. In a further example, bees use trophallaxis as a learning medium for odour signalling (Gil and De Marco 2005). This epigenetic learning occurs as the transferred liquid contains the odour used to mark the source, and the receiver associates the odour (via olfactory stimulation) with the reward. Experimentation indicated that the process was as successful as experiential learning in effectuating long-term memories with the properties of the liquid (odour and reward concentrations—the latter being sucrose solution during experimentation) affecting association intensity.

4.2.2 Honeybee dancing

When a honeybee locates a good source of nectar, it returns to the nest, noting the resource's distance from the hive and its direction with respect to the sun. On entering the hive, it performs its dance: the distance is communicated by the speed of the dance and the direction by the dance orientation (Von Frisch 1967). Several types of dance have been identified including the waggle dance described here, and experiments have indicated that the precision of the dance correlates to the availability of resources (Dornhaus and Chittka 2004). Further, Farina and Wainselboim (2005) also examined the dancing behaviour of honeybees and indicated that some honeybees, upon witnessing the dancing performed by a successful forager, engaged in stomodeal trophallaxis in order to sample the nectar quality, possibly influencing the sampling bee's decision to visit the resource.

4.2.3 Tandem calling

Tandem calling, also known as tandem recruitment, is a communication method that can be used where an insect wants a specific individual to assist with a particular task. The actual contact method can vary, and multiple strategies can be employed, including chemical signals, touch or visual cues, and often comprise a combination of stimulation signals to enable the recruitment and directional signals (De Meyer et al. 2003).

The strategy can be expanded to include many recruits, which may be led using a visual cue as stimulation followed by pheromone trail laying for guidance. This may still be considered as direct communication, since the action of following has already been stimulated, and individuals would not follow the trail without such stimulation.

4.2.4 Information centres

When animals forage unsuccessfully, it may well be in the best interest of the species that other, more successful, animals communicate likely foraging locations to them. One such communication method is the communal 'information centre' (Ward and Zahavi 1973). In this hypothesis, animals are believed to communicate successful foraging whilst visiting central communal areas allowing less successful members to follow them to the resource at a later time. Although the hypothesis has seen some controversy, evidence for its existence is accumulating. Wright et al. (2003) conducted field experiments on communities of ravens in which food carcasses were laced with coloured pellets. They noted that dominant birds feeding at the carcass would perform acrobatic displays at the communal information centre at pre-roost aggregations. Following this, increased numbers of birds would follow the lead bird to the feeding area.

5 Example behaviours

The natural world is awash with different foraging behaviours and to cover them here is beyond the scope of this work. It is worthwhile, however, to sample a few species to highlight how the some of behaviours discussed in Sections 3 and 4 are combined, and to examine some of the material available to natural computing for inspiration in developing potential search algorithms. For example, ponerine ant foraging has already been used, and the algorithm developed from it is discussed briefly in Section 6.

5.1 Ants

The many species of ants display an array of foraging behaviour; the strategies of two types of ponerine ant are described here, the army ant style foraging of the genus *Leptogenys* and the partitioned space search of *Pachycondyla apicalis*.

Maschwitz et al. (1989) studied the nocturnal foraging of the South East Asian *Leptogenys* sp.1. Their large colonies were found to forage in 3 stages termed exodus, main raid and retreat (see Fig. 2 for a depiction of the overall search pattern formed). During the exodus phase, new trails are established in narrow, tentacle-like patterns extruding from the colony's current bivouac (they are not nest builders). The outgoing traffic follows (it is assumed) pheromone trails deposited by occasional ants travelling contra-flow. Once the ants on one of the tentacles finds a suitable raiding area, that tentacle becomes very
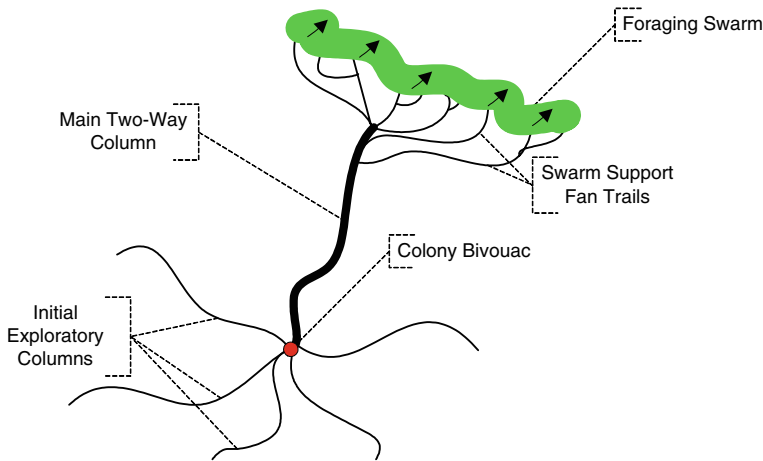
Fig. 2 Foraging behaviour of *Leptogenys* sp.1, modelled from photographs and diagrams produced by Maschwitz et al. (1989)

attractive, and the traffic rate along it increases to a peak rate of over one thousand workers per minute in a column of up to 13 ants abreast. At the column forefront, the ants spread out in an organised swarming unit to begin the raiding phase, and, as this moves forward a supporting fan shaped network of trails forms behind it. Whilst the main raid is in progress, there is a balanced flow of traffic to and from the bivouac, with the majority of homebound ants carrying food. Once the raid is complete, the swarm front turns, almost synchronously, to return to the bivouac; those ants still heading for the swarm also turn for home once the homebound flow becomes dominant. This is referred to as the retreat phase.

The foraging strategy of the ponerine ant *Pachycondyla apicalis*, from Mexico (Fresneau 1985), involves partitioning the global search area into smaller local areas. The colony members (colonies are relatively small, numbering 20 to 100 individuals) begin by setting up hunting sites roughly uniformly distributed about 10 m from the nest, each having an approximate radius of 2.5 m. Foraging ants then go out to individual hunting sites to look for prey. If they are successful, they memorise the location from landmarks and later return using these landmarks rather than the pheromone trails used by many other ant species. When ants are unsuccessful at one site, they tend to return to other previously successful sites, indicating that multiple site memory is possible. Since the system relies on landmarks, and local foraging at the hunting sites is an individual based activity, interaction among ants during foraging is limited. Occasionally, the nest is moved to another location (providing a global search aspect), using tandem calling to recruit ants from the existing nest to the new one.

5.2 Bees

Bees forage for targets (flowers containing varying amounts of nectar) that are static and generally patchy. Initial bee foraging follows an ACS strategy slightly different from that described earlier (Pyke 1978; Waddington 1980). Following a visit to a nectar rich inflorescence, a bee will fly a short distance to the next inflorescence, but direction is maintained; this, it is believed, is to avoid revisiting a site that it has depleted. When an inflorescence provides poor rewards the bee will extend its flight and increase its turn

angles to move away from the area. This response is not immediate though, and is graded according to the number of unrewarding visits made. Waddington believed this to be due to the diversity of floral distribution and therefore the low probability of being able to correctly predict the quality of surrounding inflorescences from a single visit. Experimentation indicated that this overall strategy proved most effective in high-density flora with clumped nectar distribution.

These finding were further supported in research that examined whether the strategy was evolutionary stable (Motro and Shmida 1995). This work compared the bees' strategy, termed near-far by Motro and Shmida, with several alternatives using only a single level memory (that is the response was not graded as described). The movement strategies compared were:

- *Random search*. The next location could be any of the surrounding flowers, excluding the last visited, with uniform probability.
- *Near search*. The next visited location is always the nearest flower to the last visited.
- *Far search*. The next visited is never the nearest to the last visited and is selected randomly with uniform probability.
- *Near-random search*. A combination of the first two strategies where the bee selects the nearest flower subject to sufficient reward from the last, otherwise a random flower is selected.
- *Near-far search*. This is similar to near-random except the strategy switches to a far search following a non-rewarding visit. This represents the non-graded version of the earlier work described above.

In a large area comparison with random search, the near-far strategy was shown to be most effective in an evolutionary stable environment where resources were patchy. It was also shown that the advantage increased with increased search area size. A second, smaller, area comparison that included all strategies showed that the near-far search discovered most flowers in fixed length runs in all but the shortest search, in which random search was most effective, since the resources were not depleted sufficiently for repeated visitation to be problematic. In an exhaustive search the near-far search again consistently out performed the other strategies and was shown to be an evolutionary stable strategy. The worst performer in all cases was the near search because there was a high probability of repeat visits.

Once profitable sites have been located the bees then make use of path integration to return to site hive and communicate the find to fellow bees via waggle dances.

5.3 Bacteria

Cooperative foraging behaviour is not limited to insect and high order species; bacteria have also been found to display emergent group foraging behaviours far beyond the scope of the individual. Passino (2002) drew together a wide variety of literature, in particular relating to *E. coli*, to explore the possibility of using bacterial foraging as inspiration for new techniques in distributed optimisation and control systems. Whilst the types of bacteria are numerous, it is the foraging behaviour of *E. coli* that is described here.

Physically, an *E. coli* bacterium consists of the main cell body, the pili (used for the transfer of DNA to other bacteria) and flagella (long, left-handed helix, whip-like projections that enable motor activity). When the flagella rotate counter-clockwise they are pushed forward in a swimming motion. Upon reversing the rotation, the bacterium is

pulled, causing it to tumble, allowing direction change to occur. The activities required for such movements are very efficient and, despite being in almost continuous motion, cost less than 1% of the overall energy requirements. When placed into a neutral environment, that is one without nutrients or harmful substances, the bacteria work independently, tumbling and swimming for equal time periods. Notably the swimming movement produces a Brownian motion that induces an approximate 30° wander and the independent tumbling allows the group to search, albeit in an uncoordinated fashion, for nutrients. Upon discovering the presence of a nutrient, the bacteria engage in a specialist movement behaviour known as chemotaxes. In an environment with a constant level of nutrient the chemotaxes is similar to the neutral case, except that the mean swim length and speed increase at the cost of tumbling time. When a positive nutrient gradient is encountered, this effect is further increased but only until the gradient is lost, either to a negative gradient or a flat area whereupon, after a short period, they will resume the equal swim and tumble search behaviour. In summary, the bacteria will always seek positive gradients, even in nutrient rich environments. This behaviour is reversed in the presence of a harmful substance where negative gradients are sought.

Importantly for this article, whilst bacteria do not use obvious communication strategies, emergent behaviours are produced when a collection of cells is subjected to certain conditions. An example of this is where cells are placed in a substance containing high-levels of succinate, it causes them to produce aspartate, which acts as an attractor, bringing the cells together to form a kind of swarm that moves together in a protective aggregate. Such behaviour suggests that such a basic form of indirect communication, when accompanied by the adherence to the simple set of rules described above, can produce beneficial behaviour for the whole group.

6 Discussion

Within the field of natural computing there already exist several well established paradigms that rely on individual elements working cooperatively toward a common goal; such systems are generally termed agent-based systems (a term inspired by Minsky's book, The Society of Mind, 1986). Agent-based systems are characterised by a set of computing entities that exist independently, but have a common goal, which they attempt to achieve either alone or as part of a team.

From the taxonomy of cooperation strategies indicated in Section 2, it can be seen that the type of cooperative mechanism that is employed in nature is dependent on the intended result. Agent-based systems could utilise any of the forms of cooperation, but it should be noted that the choice directly affects the overall system behaviour. It could be argued, for example, that particle swarm optimisation employs by-product mutualism and genetic algorithms use group-selected cooperation, and it is these aspects that define the very nature of the paradigms. Within the context of the cooperative strategy, the manner in which the agents' work can affect the efficiency with which the goals are achieved. Selection of specific individual roles for agents can enable more complex group goals to be achieved, but this could be at the cost of emergent behaviours, which are less likely, since systems that include agents with specific roles are generally more deterministic. Individual behaviours need not be so restrictive though—it has been seen that some animals adapt their behaviours to individual or group needs. Ants are a classic example of this, where colony members will usually perform one of a number of tasks, such as foraging, but switch to another task following environmental or internal perturbations (Waibel et al.

2006). The ability to vary behaviour could allow a system to be more adaptive and robust in hostile environments.

A wide variety of search behaviours have been briefly examined, and it has been seen that nature has adapted its behaviour to suit the prevailing conditions. Similarly, it is important for the developer of a natural computing paradigm to consider the target application and the strengths (and weaknesses) of naturally occurring behaviours before selecting an appropriate strategy. Consider, for example, a reversionary navigation system for swarming search robots in harsh environments where limited bandwidth or electromagnetic noise could hinder communication. While communication is available the robots could search in a coordinated fashion, sharing information to increase search efficiency. If the system degraded, it could be more profitable for the robots to enter individual search patterns using the strategies described earlier; an example that has already been researched as a target application of autonomous robotic swarms is mine detection (e.g. Fruergaard-Pedersen 2006). Such systems rely heavily on good communications, and loss of this facility may render the system ineffective; however, in such situations, the robots could enter a saltatory search mode to look for well hidden, patchily distributed mines. Following detection the robot may have to communicate its findings via an unconventional technique such as signalling mine position via a visual, or other, cue, perhaps inspired by the 'waggle dance'. Such use of natural metaphors could also lend itself to division of labour, which is already suggested by Fruergaard-Pedersen, where some robots could be specialist detectors whilst others could be disposable clearance drones that follow the 'waggle dance' and, once the expensively equipped detectors were clear, destroy the mine.

Two examples of how natural behaviour has already inspired natural computing paradigms are also considered in this section, the examples have deliberately been selected outside of the more established techniques, such as particle swarm optimisation to illustrate the breadth of potential for naturally inspired paradigms. The first considers how ponerine ant (*Pachycondyla apicalis*) foraging behaviour has inspired the development of a search algorithm for use in combinatorial optimisation (Monmarche et al. 2000), whilst the second examines how trophallaxis is being investigated as a potential communication strategy for miniature robots (Schmickl and Crailsheim 2006).

6.1 Ponerine ant inspired combinatorial optimisation

The natural foraging behaviour of ponerine ants consists of a global and local strategy, as previously described. The search algorithm derived from it, known as API (from *Pachycondyla APIcalis*), is as follows. An initial nest location is selected at random within the search space. Each of the ants then does one of the following: if they do not have a minimum number of hunting sites, they create one and explore it; otherwise, if the previously explored site was successful it is re-explored, and if it is unsuccessful, one of the other sites is selected at random and explored. If a site is unsuccessful for a given period of time, it is removed from the ant's memory. Tandem recruitment is then performed, in which two ants are selected at random and the performance of their best hunting sites compared. The ant with the weakest site replaces it with the strongest site of the other, in a form of elitism that assists exploitation, because it increases the number of trials in the better sites. After a set number of iterations, the nest position is moved to the group best position and the last nest move and all ant memories are erased.

The following pseudo-code describes the API algorithm (adapted from Monmarche et al. 2000, Fig. 3):

1. choose randomly the initial nest location N
2. for each ant a_i, i in 1..n:

        IF a_i has less than p hunting sites in memory
        THEN
           Create and explore a new site in the neighbourhood of N
        ELSE
           IF the previous site exploration was successful
           THEN
               Explore same site again
           ELSE
               Explore randomly selected site (among the p hunting sites in memory)

3. Remove from the ants memories all sites which have been explored unsuccessfully more than $P_{local}(a_i)$ consecutive times
4. Perform recruitment (best site copy between two randomly selected ants)
5. IF more than T iterations have been performed
   THEN
      Change nest location N to the most successful site explored and reset memories of all ants
6. Goto (2) or Stop if a stopping criterion is satisfied

Communication among the ants is limited in both the natural and artificial systems, but cooperation occurs both explicitly and implicitly. Explicit cooperation occurs via tandem running and implied cooperation occurs due the nest being moved to a location that is based on information gathered by individual ant search behaviour. Of particular interest is the note made by the API authors that the search behaviour of the ants need not be random, but can be matched to the specific problem, where landscape information is known a priori. A potential problem with the algorithm is its dependency on initialisation—in a multi-modal landscape, the group could easily be drawn away from the global optimum if the nest site is initialised to a remote local minimum.

6.2 Trophallaxis and swarming robots

Whilst the example above did not utilise extensively naturally based information sharing, many nature inspired paradigms do require complex communication solutions. Ant Colony Optimisation (Colorni et al. 1991) is one of the most widely known and successful uses of a naturally inspired communication to facilitate group behaviour, but others have been exploited.

Schmickl and Crailsheim (2006) utilised a strategy inspired by trophallaxis to maintain communication in a simulated swarm of 200 miniature robots; the aim of the research being to develop a swarm of 1,000 2 mm × 2 mm robots. The swarm communication works on the following premise: when a honeybee collects nectar from a source and flies back to the nest it will enhance its communication of its find to other nest mates using trophallaxis. As this occurs, a small amount of the crop is passed to the enquiring bee, thus bees closer to the source would be expected to have higher crop levels on a gradient basis. The robots in the simulation were working in a cleaning scenario; when a robot located dirt it collected an amount and moved away to find a dump area, this amount was stored in the robot memory. On encountering empty robots they would electronically pass an amount of

dirt thus lightening their own virtual load. The empty robots would in turn pass on any information they had regarding a dumping area. Using this technique, empty robots could follow the gradient towards the source, and a traffic system emerged. The approach has several interesting facets; sensor and communication system size can be very small, enabling small scale robots to be used effectively, and the emergent path from the dirt to the dump area was directed in that it contained no random walk behaviour even where there where obstacles along the most direct path. Furthermore, where multiple equidistant paths existed, the technique was seen to be more effective than pheromone based techniques, because all paths were used equally, distributing the traffic flow more efficiently.

7 Conclusions

The variety of behaviours found in natural systems is reflected in the vast amount of research that has only just begun to reveal the complexities that make some species so successful, even in challenging environments. As the examples have shown, the success of such species can be exploited to produce effective artificial solutions to large and/or complex computing problems, such as solving abstract mathematical problems or robot control. In keeping with Wolpert and Macready's "No Free Lunch Theorems" (1997), there is no solution that is better than any other across all problems, but there may be a given class of problem for which an optimal solution can be identified. For example, in an environment where prey items are clustered, predators have phylogenetically developed ACS strategies that maximise their exploitation of the prey behaviour. Such predatory behaviour, however, is only useful because it matches the likely distribution of the prey. If the environment becomes less predictable the predator must be able to adapt or it may well die out. The same could be argued when looking to solve novel problems: where *a priori* knowledge is available, more deterministic strategies can be employed, but where there is a paucity of such information, either more general strategies have to be applied or the agents need the ability to learn from the environment in order to be able to select or adapt a suitable strategy; where this is not possible the approach may well be sub-optimal or not succeed at all.

This paper has reviewed a range of search behaviours from the natural world, which may be used as inspiration for new approaches to computational problem solving. Some existing natural computing paradigms, such as particle swarm optimisation and ant colony systems, have already found widespread appeal and application. There remains, however, a diverse range of possibilities yet to be explored, and further work at the fringes of biology and computing may yield further profitable additions to the growing natural computing toolbox, and help address some of the very large and/or complex problems facing contemporary engineering and science.

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