

Foraging Strategies in Nature and Their Application to Swarm Robotics

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Abstract: *While foraging is a task often experimented with in swarm robotics, it is often the case that foraging strategies inspired by nature are chosen without careful consideration. This paper reviews how food acquisition is solved by various biological species including ants, termites, bees, hyenas, wolves, lions, dolphins, whales and humans. Foraging strategies including solitary foraging, behavioural matching, stigmergy, signaling to guide others and coordinated and cooperative hunting are identified and their implementation costs in robots, as well as their suitability for different scenarios is discussed. It is argued that careful consideration of a foraging task can both increase a robotic swarm's efficiency and make its implementation costs more reasonable.*

Keywords: foraging, swarm robotics, biologically inspired

1. Introduction

Biologically inspired foraging has been gaining popularity in robotics. Foraging mechanisms can be applied to many real-world tasks such as exploration, search and rescue or mining (Campo et al., 2010). For example, Campo and Dorigo (2007) simulated randomly walking robots that searched for 'food' scattered around their nest individually, while Sugawara and Watanabe (2002) used local robot-to-robot communication in order to broadcast where scattered food was located. Lee and Ahn (2006) used simulated bee-like swarm to deliver scattered food to a base. Adaptation to food availability in individually-foraging robots that relied on physical collisions and broadcasted success messages was explored by Liu et al. (2007).

It is often the case that researchers do not specify reasons behind choosing a particular animal behaviour model. It might thus seem that foraging strategies are picked at random or according whatever is currently popular. Their particular implemented foraging scenarios are of course tested and do work, but experiments with different strategies are usually lacking and it is unclear whether different biologically inspired principles would work more effectively. Exceptions include for example work of Sugawara and Watanabe (2002) who explored how strength and duration of robot-to-robot communication affected a foraging task and experiments by Drogoul and Ferber (1993) who compared efficiency of swarms where robots worked individually to those where robots formed chains to food.

In other cases, foraging of a particular species, usually ants, is picked at first and then replicated on real robots (for example Hoff et al. (2010); Schmickl and Crailsheim (2008)). While such work does show that particular algorithms could work for robotic swarms, it adds little to explain when they should be implemented.

The aim of this paper is firstly to review what types of foraging strategies exist in nature and more importantly what circumstances they are used under. The list of discussed species is by no means exhaustive but does include considerably different organisms including ants, termites, bees, fish, birds, sheep, hyenas, wolves, lions, dolphins and humans. The foraging strategies are presented in order of sophistication of collective behaviour in Sections 2 - 4 and include solitary foraging, behavioural matching, stigmergy, signaling to guide others and finally coordinated and cooperative hunting. Availability and stability of food, as well as physical capabilities of foragers are discussed.

It is argued in Section 5 that as sophistication of foraging strategies increases, robots that could use them to obtain resources as a swarm would need more sensors and actuators as well as better reasoning. It is thus important to identify the least difficult strategy necessary for a given task. The section also gives exemplary scenarios of where the individual strategies might be useful.

2. Individual foraging

The most primitive implementations belong to the individual foraging group. In solitary foraging, an individual searches for food alone (Robinson and Holmes, 1982; Darimont et al., 2003) and does not receive any information about food other than what it can itself acquire. In behavioural matching, an individual follows successful foragers and thus utilises social information (Galef and Wigmore, 1983; Fleming et al., 1992; Noble and Todd, 2002; Webster and Laland, 2012), although there is no common interest of the group and thus no interest of successful foragers to help the unsuccessful ones (Galef and Wigmore, 1983).

2.1. Solitary foraging

Most species, especially carnivores, perform solitary foraging (Gittleman, 1989). Rather than providing an exhaustive list, this section briefly discusses a number of species that were also observed foraging collectively so that conditions of solitary foraging can be identified.

Solitary foraging occurs in forest bird species if food that consists of various types of insect is infrequently scattered in very small patches, meaning that an individual needs to find many of such patches to feed sufficiently (Robinson and Holmes, 1982). Large enough prey is searched for during flight, in which case birds change their position by as little as possible so that they gain a new field of vision after feeding, making an efficient trade-off between movement and food intake. Other prey can be hidden and birds search for environmental cues like curled leaves associated with the prey in order to maximise their change of success. Thoroughness of the search increases as food becomes less abundant.

Frigatebirds that feed on infrequently scattered fish also forage solitarily, despite the fact that they live in colonies. The bird population tends to spread across foraging areas, perhaps to optimise an individual's probability of feeding (Weimerskirch et al., 2004). Furthermore, a single bird never returns to a location where it previously fed.

Tendencies to forage alone during low food abundance were found in hyenas as well (Holekamp et al., 2012). However, hyenas also choose to search for food or hunt alone when their prey is abundant but small enough for a single individual to obtain (Hayward, 2006). A similar behaviour has been found in lionesses that stalk small springhare and vulnerable neonates on their own (Stander and Albon, 1993) and in wolves that obtain easy-to-find and easy-to-catch but abundant salmon as individuals (Darimont et al., 2003). Finally, chimpanzees also act alone to catch ants (Möbius et al., 2008) or in some occasions to chase and kill small baboons (Busse, 1978).

2.2. Behavioural Matching

Behavioural matching represents a step further from purely solitary foraging as simple mechanisms

such as observing of others are used in order to socially obtain information about where food could be located. Noble and Todd identify several types of behavioural matching in relation to social information processing and learning. Social facilitation ('Do not do anything unless others are nearby') and contagious behaviour ('Seeing others do something means I am going to do it') are the most relevant to foraging. Food obtained through behavioural matching often occurs in patches and needs to be searched for (Weimerskirch et al., 2004; Webster and Laland, 2012).

Fish shoals are one of the examples where this foraging strategy is utilised. Individual fish tend to head towards places where they see other fish feed (Lachlan et al., 1998; Kendal, 2004; Ward et al., 2012; Webster and Laland, 2012) but also join large groups of similar-size fish in search for food (Lachlan et al., 1998). Furthermore, they are more likely to join when their own information about food sites is uncertain or weak (Webster and Laland, 2012) or when the cost of obtaining food based on non-social information is high (Kendal, 2004). However, a shoal does not grow indefinitely as it takes only a few leaders to split it into smaller groups. The number of fish that follow a new group non-linearly increases with the group size (Ward et al., 2012).

A similar strategy is used by sheep that need to search for profitable grass patches (Michelena et al., 2010). Like fish, sheep are attracted to large groups and can split up into subgroups when their aggregation is too large, achieving a balance between exploration and exploitation.

While fish and grazers consume their food immediately and generally stay where it was found, rats live together and gain information about profitable locations by sniffing other rats returning from foraging trips (Galef and Wigmore, 1983). Similarly, socially-foraging birds like ospreys (Flemming et al., 1992), tits, woodpeckers (Sridhar et al., 2009) or ravens (Flemming et al., 1992) head from their nests towards places where they see other birds coming from with prey. Sites where individuals aggregate and gain information about food can thus be considered as 'information centres' (Ward and Zahavi, 1973).

It is important to point out that there is no active engagement by a successful forager to communicate their experience (Galef and Wigmore, 1983) and that the information is simply available in the environment through their behaviour. Despite its simplicity, behavioural matching increases the probability of foraging success (Flemming et al., 1992; Hoogland, 1981) by decreasing the risk of individual-based errors (Ward et al., 2012). Furthermore, the cost of environmental sampling is decreased compared to solitary foraging (Flemming et al., 1992; Webster and Laland, 2012).

3. Recruited individual foraging

During recruited foraging, an individual that is a part of a colony obtains food either for itself or for other colony members. Unlike in individual foraging, the whole colony can benefit from success of a single member. Various tactile, chemical or visual cues are thus passed between group members in order to distribute collective knowledge about where food can be located.

Recruited foraging is typical for insect colonies where food is aggregated and then distributed according to social status of the colony members (Ward et al., 2012). In this context, a group as a whole can be understood as both an information processing and a food consuming unit, in contrast with aggregates of fish or birds that do facilitate social information but are only dependent on themselves for food acquisition.

3.1. Stigmergy

Several species use the environment in order to store information, most notably ants and termites. These insects are capable of laying chemical pheromone trails when they find food and these trails are then followed by other colony members with a probability that increases with the trail strength. (Beekman, 2001; Arab et al., 2012). Food of these species appears in patches and the colonies obtaining it need to be large enough (Beekman, 2001; Barbani, 2003) as a lot of interactions between group

members are required (Berthouze and Lorenzi, 2008). The individuals are often blind and will follow a trail to their death (Ribeiro et al., 2009), but facilitation of stigmergy was also observed next to using visual cues, gravity, magnetic field (Ribeiro et al., 2009), odor sensing or following shape of a traversed environment (Barbani, 2003). Apart from navigation towards a food source, army ants also use pheromones to rapidly recruit nest mates for a raid (Witte and Maschwitz, 2002).

Some insects have an especially complicated repertoire of pheromones. The main foraging pheromone is often very volatile but strong and thus rapidly attracts individuals (Arab et al., 2012). Its relatively quick evaporation rate assures a negative feedback to the recruitment (Grace and Campora, 2005; Ratnieks, 2008) and prevents travelling to locations where a source has been depleted. Furthermore, both ants and termites use weak but long-lasting pheromone while exploring, probably to keep a ‘memory’ of the environment utilised to easily reevaluate previously depleted food patches or in order to build up a recruitment trail quickly when food is found (Beekman, 2001; Arab et al., 2012). Finally, Pharaoh ants also use a ‘no-entry’ pheromone that signals others not to follow an established branch of a trail network, allowing a colony to stop following a branch quicker than pheromone evaporation rate allows (Robinson et al., 2005).

Apart from food quality, direction to the nest is also encoded in the trails. Ants can perceive angles between branches and head either towards or away from the nest (Robinson et al., 2005; Berthouze and Lorenzi, 2008). On the other hand, termites place special long-lived chemicals into their pheromone trails in order to orientate themselves (Arab et al., 2012; Grace and Campora, 2005).

It is notable that the information propagation time has a significant impact on success of stigmergy. Firstly, Sumpter and Beekman (2003) showed that trails to a better food source in ants simply take less time to build up. Their experiments thus suggest that if trail establishment was very fast or immediate (for example if ants were able to shout to their nest mates), the colony would not be able to distinguish a

good source from a bad one. On the other hand, the dependence on time means that it is hard for a colony to create a new better route to a food source when such an opportunity arises (Ribeiro et al., 2009).

Another factor that affects stigmergic foraging is the number of individuals following a trail. Ants tend to push each other away if there are too many of them at an intersection, which results in creation of additional non-optimal paths (Dussutour et al., 2004).

3.2. Signalling to guide others

Another type of recruitment strategy involves direct signaling between individuals. Unlike stigmergy, signaling requires both the signaller and the receiver to be present at the same time, but the environment no longer needs to be altered by trails.

Recruitment by touching antennae has been observed in ant colonies that are small (Beekman, 2001) or forage for food that is scattered by wind as opposed to occurring in patches (Prabhakar et al., 2012). When foragers return to the nest, they drop food and wait at the entrance to exchange information with other returning foragers. In some cases, such a direct contact is even used to enforce pheromone trail following (Beekman, 2001). Similarly to stigmergy, a richer and easier-to-obtain food has a higher frequency of returning foragers and it thus attracts more ants. However, unlike in stigmergy, non-linear effects like structure of a nest may influence the way that information is distributed (Prabhakar et al., 2012).

Some signaling does not require direct contact to work. Termites use acoustic cues to inform others about size of a wood patch they find. Since they live where they feed, they need to enforce their stigmergic trails by additional information as their pheromone network alone is not specific enough (Inta et al., 2007; Evans et al., 2007). Ospreys were also found to use vocal cues in order to recruit foraging partners (Flemming et al., 1992).

Signalling about a food source is most often associated with bees that use dancing in order to transfer information. In contrast with ants and termites, bees depend on flowers quality of which can change rapidly (Granovskiy et al., 2012) and have evolved to be able to switch quickly to a newly discovered and better

food source (Vries and Biesmeijer, 2002). The techniques they use include recruitment by waggle dance that encodes both food quality and location (Seeley, 1994), scouting (Biesmeijer and de Vries, 2001; Seeley, 1992) and inspection (Granovskiy et al., 2012) that allow for effective exploration of the environment and passive colony nectar intake sampling combined with tremble dancing that can adaptively change the colony's nectar processing rate (Seeley, 1992; Vries and Biesmeijer, 2002).

Bee colonies have a generally more complicated labor division and a single bee can have different tasks during its life time (Biesmeijer and de Vries, 2001). Scout bees that represent a fraction of a colony explore the environment, searching for nectar. When they return to the nest with information about a new source, they perform waggle dance near the nest entrance in order to recruit others (Biesmeijer and de Vries, 2001; Seeley, 1992). Free bees observe the signal and can become foragers themselves if the signalled quality reaches a certain threshold (Seeley, 1994). Bees adapt this threshold with respect to current food availability, increasing the flexibility of recruitment.

The waggle dance is a complicated signal as it contains both qualitative and spatial information about a food source. Profitability of food is encoded by strength and length of a dance (Seeley, 1994; Granovskiy et al., 2012). A recruiter that advertises a more profitable food source moves across the dance floor for a longer time, and thus meets and recruits more bees. The source location is encoded in the technique and position of the dance within the nest (Seeley, 1994). However, this encoding is not perfect and some bees get lost when they search for the suggested patch, effectively becoming scouts and exploring the environment for more sources.

Returning foragers pass nectar to other bees that process it deeper in the nest (Huang and Seeley, 2003) Foragers passively sample the colony's nectar intake rate by evaluating how quickly they are able to pass their load on. If the speed is unsatisfactory or if it is not possible to unload the nectar at all, a forager starts performing a tremble dance, moving deeper inside the nest and trying to recruit other

nectar processing bees (Seeley, 1992; Vries and Biesmeijer, 2002). Rather than becoming active immediately, new recruits touch the tremble dancer with their antennae (Seeley, 1992), as if to confirm that they received the message.

Foragers become unemployed and remain in the nest if a food source is either depleted or very poor or when a colony cannot cope with nectar intake (Biesmeijer and de Vries, 2001). They can be re-recruited by nest mates and they prefer familiar foraging sites, unless newly discovered sites have a better quality or promise energy return with a higher certainty (Wray et al., 2011). Alternatively, unemployed bees can become inspectors and return to their old foraging site in order to re-evaluate it. Inspection, similarly than scouting, allows the colony to effectively switch between sources of changing quality (Granovskiy et al., 2012).

4. Group hunting

In contrast with recruited and individual foraging, strategies belonging to the group hunting category require multiple individuals to obtain the same food item collectively by either coordination or cooperation. Engagement in a group hunt means that an individual does not have to rely on food sources of lower profitability (Hoogland, 1981; Skinner et al., 1995; Hayward, 2006; Smith, 2010). The prey is either larger or faster than the hunter itself, as it is for example the case in lions (Stander and Albon, 1993) or hyenas (Hayward, 2006). Alternatively, the nature of the food distribution may simply mean that the energetic return from foraging is higher when performed in a group, which for instance is the case for dolphins (Benoit-Bird and Au, 2009b), some Belukha whales (Bel'kovitch and Sh'ekotov, 1993) or humans (Bliege Bird et al., 2001).

4.1. Coordinated hunting

The most primitive form of collective hunting is hunting by coordination where no direct signals are passed to group members during the hunt. While chimpanzees tend to hunt either opportunistically or

search for prey when they travel in groups (Newton-Fisher, 2007), spotted hyenas were observed to assemble at a den before the hunt seemingly to agree what exactly they will catch (Hayward, 2006)

In some species, the prey is chased by group members that are only trying to maximise their own chance of obtaining it and thus use minimal coordination, as it is the case in chimpanzees preying on monkeys (Busse, 1978; Newton-Fisher, 2007) or hyenas that chase weak members of ungulate herds (Hayward, 2006). Alternatively, some chimpanzees (Newton-Fisher, 2007) and lions (Stander and Albon, 1993) may take specific roles during the hunt and coordinate their behaviour more precisely.

When it comes to sharing a kill between hyenas or chimpanzees, a group member's social status determined by its strength or kinship to other high-status individuals decides how much food it gets (Holekamp et al., 2012; Newton-Fisher, 2007). Chimpanzees tend to also fight for the kill (Busse, 1978), unless a single male takes the whole prey and distributes it to other males for alliance or to females for sex (Newton-Fisher, 2007), using the meat as a commodity rather than a source of nourishment.

4.2. Cooperative hunting

Cooperation is defined as interaction via collective action between individuals that increases their fitness despite the potential cost of such action (Busse, 1978; Dugatkin et al., 1992). In contrast with coordinated hunting where group members seek to obtain the food for themselves while facilitating actions of others, cooperating individuals actively synchronise their behaviour in order to increase the whole group's chance of success. Cooperative hunting thus requires not only established hunting roles and more sophisticated signaling but also rules of how food can be fairly shared (Benoit-Bird and Au, 2009a; Smith, 2010).

Dolphins are one example of species that uses cooperation for acquisition of small prey like lanternfish or shrimp (Benoit-Bird and Au, 2009a). Their food is abundant but scattered, meaning that they are limited by their feeding efficiency rather than availability of prey. In order to deal with this problem, these

mammals coordinate very precisely to progressively create and tighten a circle around small prey items, gradually herding them together. Individuals then take turns feeding from the created locations of high prey density. Benoit-Bird and Au (2009b) observed that dolphins use short-distance but efficient click sounds during changing of formations throughout the coordinated hunt, although it is unclear whether the sounds are directed at specific individuals. Nevertheless, it is evident that compared to lions, hyenas or chimpanzees, dolphins use more sophisticated coordination via signaling, allowing them to create hunting parties of up to 27 individuals (Benoit-Bird and Au, 2009a). Similar group hunting behaviour was observed in Belukha whales that use echolocation pulses as they cooperatively herd fish together and then feed on them (Bel'kovitch and Sh'ekotov, 1993).

Humans are a species that mastered group hunting during their evolutionary history. Similarly to other animals that forage in groups, we prefer prey that has high energetic return rate (Bliege Bird et al., 2001). However, our intellectual, linguistic (Smith, 2010) and empathic (Delton and Robertson, 2012) capabilities allow us to not only effectively coordinate with each other during obtaining of food (Bliege Bird et al., 2001) but also to create resource pools where non-successful foragers can get food as long as they are willing to contribute when they are successful as well (Smith, 2010).

Resource pooling works because we evaluate others for a long period of time and select our foraging partners based on their psychological attributes like tendency for altruism and honesty rather than on short-term return rates (Delton and Robertson, 2012) or strength as seen in hyenas (Holekamp et al., 2012) and chimpanzees (Busse, 1978). Humans tend to partner with individuals whose whose cost of sharing or obtaining food is at least as high their own (Delton and Robertson, 2012).

During a cooperative action, we tend to rely on centralised strategies (Furniss, 1974; Dekker, 2006). For example, primitive hunt societies designate experienced hunters to become hunt leaders who coordinate actions of all hunt participants (Bliege Bird et al., 2001). Leaders receive the highest reward and

are perceived by their tribe as fully responsible for outcome of a hunt. This type of behaviour, as well as our superior communication skills, facilitate easy social learning (Smith, 2010) as the knowledge of an experienced individual is present during the hunt even if the person is not as agile as his younger counterparts.

5. Application to robotics

The above review of foraging strategies and animals that use them indicates that the choice of how to obtain food does not depend as much on species as it depends on niche the organisms find themselves in. Members of the same species will forage solitarily if that is what brings them the highest energetic return. On occasions when food is hard to obtain for an individual, group foraging occurs and its benefit grows with group size until a threshold is reached when a too large aggregate cannot obtain enough food and it needs to split up (Vucetich et al., 2004; Michelena et al., 2010; Ward et al., 2012).

If evolution has solved the problem of foraging optimisation under different scenarios, it is reasonable to take inspiration from nature when thinking about building foraging robotic swarms. This section firstly looks at implementation costs of the above discussed strategies and follows with categorisation of scenarios under which they might be used by robots.

5.1. Implementation costs

As the complexity of group behaviour increases, more sensors, actuators and reasoning about the environment is generally needed. Table 1 gives an overview of implementation requirements for hypothetical robots using the individual foraging strategies.

In the least complicated scenario, each robot forages solitarily and is only equipped with sensors and actuators that need to deal with navigation and resource acquisition, such as infrared sensors used for obstacle detection, light sensors used for locating a base, motors, grippers, etc. (Drogoul and Ferber, 1993; Campo and Dorigo, 2007; Lee and Ahn, 2006). However, such a swarm cannot rely on cancelling out

of individual errors as it is the case in large groups that utilise social foraging (Ward et al., 2012) and individuals must generally spend more time searching for a resource (Webster and Laland, 2012). In cases of low resource abundance, it is also useful if a robot remembers where it foraged before and does not return to the same place twice, similarly to frigatebirds (Weimerskirch et al., 2004).

Some social information can be transmitted during behavioural matching, while the sensors and actuators of robots remain relatively simple, considering that no direct signaling between robots needs to be implemented (Galef and Wigmore, 1983). However, it is generally required that individuals move together as a group similarly to fish (Ward et al., 2012; Webster and Laland, 2012) or sheep (Michelena et al., 2010) or that they aggregate on a place where social information can be shared like birds (Flemming et al., 1992; Sridhar et al., 2009) or rats (Galef and Wigmore, 1983) do. Such capabilities require sensors and reasoning modules able to identify other robots and their behavioural cues. Furthermore, information obtained by observation of successful foragers returning to the base can potentially be faulty as it is not guaranteed that a successful forager returned by following a straight line.

A more precise information encoding is possible by using stigmergy where a collectively generated trail directly points to a resource. However, such recruitment requires more costly sensors and actuators, careful design of how artificial pheromone is to be encoded and decoded, as well as inclusion of the pheromone in a robot's decision making processes. Furthermore, while there is no need for group members to meet or recognise each other in order to exchange information, the artificial pheromone needs to be somehow stored in the environment. This could prove difficult to implement for robotic swarms, especially if they operated in human-inhabited environments, although attempts to create stigmergy-like trails by using special robots that represented pheromone (Ducatelle et al., 2011) or by using light projections on the ground (Sugawara et al., 2004) have been made.

Information propagation time could be an issue

Table 1: Implementation requirements of foraging strategies

Foraging strategy	Inputs	Outputs
Solitary	- Navigation and resource recognition	- Navigation and resource manipulation
Behavioural matching	- Navigation and resource recognition - Recognition of others - Behavioural cues recognition and understanding	- Navigation and resource manipulation
Stigmergy	- Navigation and resource recognition - Artificial pheromone recognition and understanding	- Navigation and resource manipulation - Artificial pheromone secretion
Signaling to guide	- Navigation and resource recognition - Recognition of others - Signal recognition and understanding	- Navigation and resource manipulation - Signal creation
Coordinated foraging	- Navigation and resource recognition - Recognition of others - Recognition and understanding of behavioural roles - Recognition and understanding of recruitment signal	- Navigation and resource manipulation - Creation of recruitment signal
Cooperative foraging	- Navigation and resource recognition - Recognition of others - Recognition and understanding of behavioural roles - Recognition and understanding of recruitment signal - Recognition and understanding of action signals - Rules of when consuming resource is allowed	- Navigation and resource manipulation - Creation of recruitment signal - Creation of action signals

as well. Ants that use pheromone trails are unable to switch to a better path alternative once a trail has been established (Ribeiro et al., 2009), but the trail needs to be built up gradually so that an initial choice between sources of different quality can be made (Sumpter and Beekman, 2003). Finally, live experiments of Beekman (2001) and Barbani (2003) and the model of Berthouze and Lorenzi (2008) suggested that a colony must be large enough to be able to use stigmergy effectively. It is thus possible that stigmergy would only work effectively for large swarms of foraging and pheromone-storing robots working together.

Most of the problems of stigmergy including the need to edit the environment and slow information

propagation times could be solved by using direct signaling to recruit others. Such is the case in small ant colonies (Beekman, 2001) and bee hives (Seeley, 1992; Biesmeijer and de Vries, 2001; Huang and Seeley, 2003; Vries and Biesmeijer, 2002; Granovskiy et al., 2012). The enhanced effectiveness of signaling comes with the need of individuals to meet and communicate with each other, combining the cost of sensors and programming required in behavioural matching for recognition of group members, and sensors, actuators and reasoning modules used in stigmergy for signal propagation and understanding.

Even more complicated implementation is required for robots that need to coordinate their actions in order to obtain a resource. Similarly than in the pre-

viously discussed strategies, robots need to recognise group members, as well as create and understand a recruitment signal that initiates cooperation. However, reasoning about actions of others needs to become deeper than simple recognition of behavioural cues as it is the case in behavioural matching (Noble and Todd, 2002), especially if different roles are to be taken by different group members.

If more precise cooperation that includes signaling during resource acquisition is required, signals about a robot's current action and perhaps about the next planned action need to be transmitted and understood by the rest of the swarm. While cooperative foraging is superior to other strategies when resources are difficult to obtain, its implementation cost could become high.

5.2. Practical questions

Once it has been established that a choice of implemented foraging strategy changes the cost of building a robotic swarm, it is useful to look for situations in nature when strategies with lower implementation costs can be useful. A proposed decision tree based on questions about the nature of a resource and of a foraging task is showed in Figure 1.

The first obvious question to ask is whether the resource can be obtained by an individual itself. For example, some raw resources can be extracted by single robots, while carrying of large unbreakable stones might require coordinated actions. In cases when a resource can be handled by a single individual, its density and availability should be taken into consideration. Based on the examples of birds (Robinson and Holmes, 1982; Weimerskirch et al., 2004), lions (Stander and Albon, 1993), hyenas (Hayward, 2006; Holekamp et al., 2012), wolves (Darimont et al., 2003) and chimpanzees (Busse, 1978; Möbius et al., 2008), solitary foraging should be implemented for resources with high abundance, such as solar energy or wood in a forest, or when a resource is distributed randomly and scarcely so multiple robots would not do any better collecting it, like when pieces of rubbish need to be removed from a street.

In contrast, resources that occur in patches are best handled by groups where at least some level of infor-

mation exchange is present. As the predictability of a stable resource decreases, quicker response time afforded by signaling (Vries and Biesmeijer, 2002) and higher flexibility delivered by inspection of previous foraging sites and scouting for new ones (Biesmeijer and de Vries, 2001; Granovski et al., 2012) should become more optimal to implement. For example, wood, fruit and other food consumed by termites (Grace and Campora, 2005) or ants (Barbani, 2003; Beekman, 2001; Ribeiro et al., 2009) tends to remain as it is until it is consumed by the colony. Similarly, raw resources are stable and stigmergy should thus be sufficient to implement in a robotic swarm that collects them provided that the problem of how to store the information in the environment is solved. On the other hand, robot colonies that need to harvest a stable resource quality of which depends on external factors like the weather should be equipped with more adaptive bee-like behaviour. However, non-linear effects of how individuals move and therefore meet (Prabhakar et al., 2012) should be taken into account in such scenarios. Furthermore, lower precision of a signal that comes from a single individual as opposed to a pheromone accumulated via actions of many should also be considered by potential robotic recruits.

Both stigmergy and signaling to guide others are types of foraging strategies that involve recruitment and are thus suitable for resources that generally do not move and are not depleted quickly. A stigmergic trail especially can provide a 'map' of the environment and guide any member of a colony to the resource or indicate unexplored locations. However, certain types of resources, while occurring in patches are unstable or deplete quickly. Recruiting more swarm members would waste energy that could be used for exploration and behavioural matching should thus be implemented instead. Such is the case in birds that catch fish (Flemming et al., 1992) or feed on dead animals (Loman and Tamm, 1980), rats that eat small food items scattered around their nest (Galef and Wigmore, 1983) or sheep that consume plants (Michelena et al., 2010). Similarly, robots that for example collect rain water concentrated in easily diminished puddles should not actively aggregate

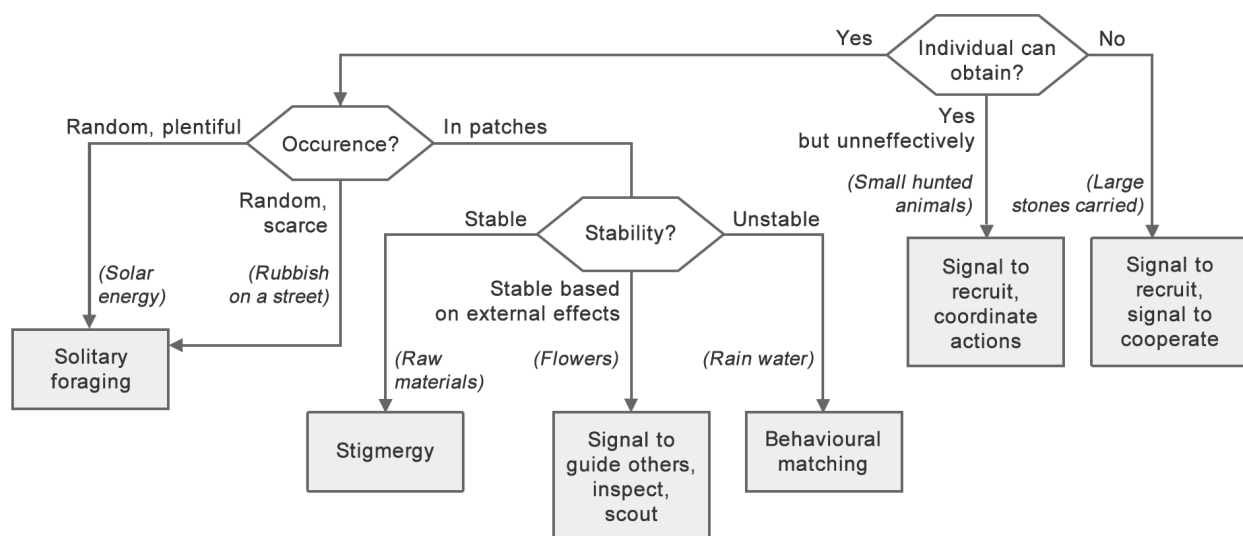


Figure 1: Foraging strategy decision tree

near one resource patch but observe others and only acquire social information opportunistically.

When a resource could be foraged for by a single robot but presence of other group members would increase the chance of acquiring it, coordination of actions should be considered as the less costly group resource acquisition strategy. Similarly to hyenas (Hayward, 2006), lions (Stander and Albon, 1993) or chimpanzees (Busse, 1978; Newton-Fisher, 2007; Hayward, 2006), robotic hunters foraging for small or weak animals could find coordination useful.

In contrast, when an animal that could overpower the robots would be targeted or simply when a resource like a stone too large to be carried by a single robot would need to be obtained, a more direct cooperation that includes passing of signals (Benoit-Bird and Au, 2009b) might be necessary.

An interesting strategy not shown on Figure 1 is resource pooling. Resources are aggregated and distributed to members of insect colonies (Ward et al., 2012) and human tribes (Delton and Robertson, 2012) in order to minimise the impact of changing food availability on an individual. While social structure and fairness of food distribution are issues

preventing resource pooling from being more widely used by biological systems (Ward et al., 2012), robots could simply be programmed to only take what they need and when they need it. Resource pooling could thus be added on top of any other foraging strategy if energy of robots depended on a variable resource like insects or water in a desert.

5.3. Future work

The arguments of this paper depend on literature considering different organisms like ants, bees, termites, fish, birds and mammals. It is however possible that a wider review would help to identify more foraging strategies or more details about the strategies discussed here.

The assumptions about foraging niche as well implementation costs of foraging robotic swarms presented in Section 5 need to be validated firstly in simulation and then on real robots. Simulated but realistic agents with different levels of collective foraging should be implemented and their effectiveness compared for various resource types. Furthermore, at least a selected portion of the experiments should be replicated in physical robots as circumstances ne-

glected in simulation might impact applicability of the results. Foraging is a real world task and should thus be optimised for real world scenarios.

It would be also interesting to see whether the individual strategies can be autonomously switched between by robots. For example, the occurrence and stability of a resource could be evaluated on-line and agents could agree to start searching in groups or start recruiting to resources that appear in large patches. Such an adaptive algorithm would very probably be superior to any single foraging strategy.

6. Conclusion

A number of approaches to foraging found in nature were discussed, including solitary foraging used when resources are easy to obtain or very scarce, behavioural matching where individuals gain information from successful foragers without communication between the two, stigmergy where chemical substances in the environment are used for recruitment of group members, recruitment through signaling that tends to be more flexible than stigmergy and group hunting strategies where individuals coordinate their actions in order to more effectively obtain a prey or cooperate using signals when prey is impossible to acquire by a single individual.

It was argued that the sophistication of foraging robots both in terms of their sensors and actuators as well as their reasoning abilities would need to increase as a resource would become more difficult to obtain and handle. It therefore seems reasonable to think about the least difficult strategy that is necessary for a given task before time and money is spent ineffectively. For example, a colony of solar-powered robots gathering ore could use a form of stigmergy for the collection, while getting their freely available energy solitarily. However, if sun light became less evenly distributed, for example in thick forests or dense urban environments, behavioural matching or even active recruitment would need to be implemented so that the robots could survive. More sophisticated cooperation and coordination would only need to be used if the robots were to hunt prey or manipulate large heavy objects, especially if they also depended

on such a resource for their own energy.

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