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Fast, Cheap, and Self-organized:
How the Study of Social Insects Inspires Collective Robotics

"What is it that governs here? What is it that issues orders, foresees the future, elaborates plans, and preserves equilibrium?" --Maurice Maeterlinck

I. Self-Organization

The term 'self-organization' describes "the process by which individuals organize their communal behaviour to create global order by interactions amongst themselves rather than through external intervention or instruction" (Willshaw, 2006). Self-organization is at work where a structure or pattern appears in the absence of central control, as a result of actions of a multitude of individuals. It is therefore linked to, and sometimes conflated with, emergence - complex systems exhibiting characteristics that cannot be predicted from the analysis of their parts alone. Examples of self-organization abound in nature, ranging from physics, where it is responsible for the uncanny forms of crystals, to biology, where it can be found in spontaneous protein folding, or the flocking behaviour of birds in a swarm. The concept has also found its application in the social sciences, although to much greater controversy. In particular, the processes by which prices emerge in an unregulated market have been described as an instance of self-organisation. Economist Friedrich Hayek introduces the term "catallaxy", meant to replace an 'economics' deemed inaccurate for its regulatory implications, as describing "the order brought about by the mutual adjustment of many individual economies in a market" (Hayek, 1976). More recently, self-organization has informed research into social media and other phenomena of the 'networked information environment' (Benkler, 2006).

In computer science and engineering, self-organization is of interest in the context of autonomous agent-based models. While research in this field as focused on developing "truly autonomous mobile robots", purely virtual software agents exist as well and have significant relevance in scientific applications (Austin et al., 2006). The bottom-up approach to cognition that informs autonomous agents was pioneered in a series of papers by Rodney Brooks (1985, 1986), who also coined the catchphrase "fast, cheap and out of control" for robots modelled after r-selected social insects (Brooks & Flynn, 1989). As Austin et al. (2006) summarize, this approach to complex adaptive systems "presumes that displays of intelligence are the product of complex interactions between an agent’s behavioural repertoire and its environment, where that agent’s behavioural repertoire is itself the product of the non-linear system formed from multiple interacting behaviour generating modules within the agent." Brooks' proposed that this approach would provide advantages in adaptability and robust operation, in particular in unstable and quickly changing environments (cited in Austin et al., 2006).

This paper investigates how an understanding of self-organization in social insects, and particularly ants, has inspired design strategies for multi-robot systems. In the following, part II describes several concepts from research on ant behaviour, and part III shows how these have been applied in robotics. Part IV concludes.

II. Social Insects

Ants, termites, as well as many species of bees and wasps, are so-called eusocial insects (two species of mole rats are the only mammals known to be eusocial). Ants, in particular, perform strikingly complex tasks requiring cooperation between large counts of individuals. Leafcutter ants (Atta), for example, cut leaves from plants to grow nutritious fungi. To transport the leaves to their nest, they organize trails to and from foraging sites, often spanning hundreds of meters (Hölldobler & Wilson, 1990), and even building tunnels (Gordon, 2010). And workers of weaver ant (Oecophylla) colonies building a nest pull stiff leafs together by forming chains with their own bodies, which allows them to bridge wide gaps. Joining several chains together, they create enough force to pull leaves edges together, which can then be connected with a continuous thread of silk emitted by a mature larva held by a worker (Hölldobler & Wilson, 1990). Still, individual ants - although famed for their relative strength - have simple individual characteristics.

Naturalists have marvelled at the organization of ant colonies for centuries, as the prefatory quote by the Nobel-prize winning poet Maurice Maeterlinck exemplifies, and many have been quick at hand with fascinating explanations. But as Diane M. Rodgers (2008) has shown, the observers all too often projected their own believes about human societies on the insects - such as the French revolutionary Latreille, who rejected the common view of an ant "queen" and subjugated workers, arguing that the colony has "a single will, a single law" based on the love each ant feels for the others (quoted in Gordon, 2010). Despite this anti-monarchist intermezzo, for the longest time ants colonies - and with them all eusocial insects - were seen as hierarchical organizations similar to a kingdom, a view that still persists in popular culture (Gordon, 2010).

Modern ant studies commenced in the 1960s, when evolutionary biology "took up an economic, free-market perspective with a vengeance" (Gordon, 2010). It is closely linked to the name of E. O. Wilson, the Pulitzer Prize-winning biologist. Drawing on the advancements of cybernetics, Wilson developed an understanding of ant colony behaviour as a mechanical process, much like a Taylorized factory. According to this view, ants are genetically programmed to perform certain acts over and over again, led in their direction by environmental cues (Hölldobler & Wilson, 1990).

Wilson postulated that ants were genetically programmed to perform different tasks over and over again. In some polymorphic ant species, differences in anatomy seem to organize division of labour (Bonabeau et al., 1999). But also in ants that are not polymorphic, different "jobs" can be observed. In the red harvester ants (pogonomyrex barbatus) studied by Gordon (2010), four different occupations taking place outside the nest can be distinguished: patrolling, foraging, nest maintenance, and midden work. According to Wilson's view, these jobs would be performed by different "castes" of ants, which would be fixed over the life span as a result of genetic programming. In performing their tasks, he thought, ants were guided by fixed chemical cues acting as triggers for their pre-programmed instructions. Working with mathematical optimisation models, Wilson then described how natural selection would tune such a system to produce, in each species, the right among of ants required by the environment (Oster & Wilson, 1978).

Since the early 1990s, however, it has emerged that ants behave much less fixed than was previously believed. As Deborah M. Gordon (2010) puts it, "an ant colony's behavior is guided by a pulsing, shifting web of interactions" rather than a predefined genetic program. According to this 'emergent' view, the behaviour of individual ants is heavily dependent on their encounters with their nest mates, pheromone trails left by these, and environmental cues, not simply on its own innate characteristics. This results in a changing research question, as Gordon (ibid.) writes: "Instead of asking how the colony evolves to have a static, optimal distribution of specialized workers, we need to ask how the colony evolves the moment-to-moment regulation that gets the necessary numbers of workers into each task according to current conditions."

Ants can react to two kinds of external information: changes in the environment, and interactions with each other. The latter are either direct - and then mostly tactile - or indirect, e.g. through pheromone trails left by patrollers (Gordon, 2010). Such trails, which send out a 'follow' signal to other ants, are an instance of stigmergy - "a way of storing information in the environment, and using it as a means of indirect communication" (Werfel, 2006). Some ants use pheromone trails to 'recruit' others to a promising foraging site. Such a positive feedback mechanism (Bonabeau et al., 1999) starts a directed movement - as a research team around Jean-Louis Deneubourg noticed, in a way analogous to self-organization at work in irreversible thermodynamics (cited in Gordon, 2010).

Gordon (2010) presents compelling evidence that task allocation is a dynamic process guided by interaction networks: ants decide what to do on the basis of their recent experiences. What matters in this process is action rate, not content, writes Gordon: "The pattern of interactions itself, rather than any signal transferred, acts as the message. What matters is not what one ant tells another when they meet, but simply that they meet". It seems as if ants react to these interactions according to a set of probabilistic rules, which might affect two variables or internal states of the ant: its last job, and whether it is currently active or idle. For example, an idle ant might encounter foragers returning to the nest; the rate at which successful foragers return would then provide an estimate for food availability.

To summarize, recent research into the behaviour of social insects suggests that the order found in ant colonies is an emergent phenomenon. It results from the interaction of many similar 'components' (i.e. ants), which react to each other, as well as cues in the environment. In varying circumstances, the ants' innate 'rule sets' evoke different courses of action, probably on a probabilistic basis. This way, ant colonies are able to react quickly and flexibly to environmental changes. At the same time, the lack of a commando 'bottleneck' typically found in hierarchical organizations, and the reliance on interaction rates (i.e. redundancy) provides robust operations.

III. Bio-Inspired Collective Robotics

Various engineering fields draw on concepts and metaphors from biology. Collective robotics, in particular, has taken up ideas from the study of social insects, while the related field of amorphous robotics (more interested in nano robotics for application in e.g. 'intelligent wall paint') has taken its leads from neurobiology (Abelson et al., 1996). The bio-inspired bottom-up approach to artificial intelligence (AI) was pioneered by Brooks (1985, 1986) as an alternative to the top-down logic-based strategies previously prevalent in AI research.

Brooks (1985, 1986) proposed large numbers of small, inexpensive robots modelled after r-selected insects such as ants as a replacement for larger, more costly singular robots, with the expectation of higher adaptability and more robust operation. Similarly, Werfel (2006) suggests that "swarm systems" would be characterized by robustness to robot loss, decentralization eliminating the need for reliable communication along any hierarchy, parallelism enabling the system to work faster than in a more sequential mode, and simplicity in design, reducing the risk of malfunction. Yu (2010) also notes the advantages of self-organizing multi-agent systems in scalability, as they don't rely on hierarchical structures which, with scale, increase quickly in complexity.

Jones and Mataric (2004) provide a useful framework to distinguish different types of multi robot systems, with three characteristics: use of deterministic or probabilistic action selection, use of internal states or not, and capable or incapable of inter-robot communication. Applying this framework to Gordon's (2010) research on ants, we could classify social insects as using probabilistic action selection, not maintaining internal states, and capable of inter-agent communication (although this latter point might necessitate more than a yes or no answer, since the content of this communication is less important than its frequency). Wilson's earlier view differs greatly from that, as it characterizes ants at using deterministic action selection, maintaining internal states, but not being able of (substantial) inter-agent communication (Hölldobler & Wilson, 1990).

Early robots inspired by social insects were based on the view propagated by E. O. Wilson and his contemporaries. Central to the "fast, cheap and out of control" robots promoted by Brooks and Flynn (1989) is the lack of a "central world model" (as common in logic-based AI). Instead, the robots were programmed with a small set of "layers of control" or heuristics, which are triggered by environmental cues, as is exemplified by the teams smallest product, Squirt: "His normal mode of operation is to act as a “bug”, hiding in dark comers-and venturing out in the direction of noises, only after the noises are long gone, looking for a new place to hide near where the previous set of noises came from." Other robots were equipped with better sensors and more computing more, so as to pursue more complex tasks such as "to wander around office areas, go into people's offices and steal empty soda cans from their desks". However, these robots could not engage in collective behaviour.

An early instance of collective robotics based on social insects comes from Kube and Zhang (1993), who understand the behaviour of social insects as being "like a stored program whose execution is a result of specific sensory stimuli", clearly echoing Wilson's genetics-and-pheromones approach. Kube and Zhang aimed to create a "synergistic robot system" in which homogeneous robots would "function collectively in groups" when working towards a cooperative collaborative task: the pushing of boxes to heavy for a single robots. Their robots were programmed with five behaviours linked to sensors and actuators, namely "a goal behavior directing the robot towards the box, an avoid behavior to handle collisions, a follow behavior allowing a robot to follow another, a slow behavior which adjusts motor speed preventing rear-end collisions, and a find behavior used in exploration". The 'follow' behaviour, in particular, was an adaptation of the processes that enable self-organization in ants; otherwise, however, the robots were not enabled to directly communicate. Consequently, while the robots were able to collectively perform the box-pushing task, Kube and Zhang noted the necessity of progress monitoring behaviour which would prevent stagnation and cyclic behaviour.

Another feature of ant behaviour is explored in the work of Justin Werfel (2006), who extended the use of stigmergy in a collective construction task. Collective construction of specific buildings is particularly challenging because it starts out with a high-level plan of the desired outcome, rather than a low-level set of rules. In Werfel's project, robots were programmed to pick up building blocks, carry them to a construction site, and attach them so that in the end the desired construction would be built. To achieve this, Werfel introduced "extended stigmergy", enabling the robots to localize their position in relation to the construction. While thus augmenting the use of environmental cues common among ants, this concept did not utilize communication among the agents and following behaviour, which seems to be at work in ants' construction project, e.g. in weaver ants.

A more recent dissertation by Chih-Han Yu (2010) describes a networked multi-agent system, in which global tasks are achieved by local communication and cooperation with direct neighbours. As Yu writes, "in this framework, the multiagent tasks are described as a set of inter-agent state or sensor constraints (differences), e.g., as the desired sensor difference between neighboring agents, and each agent iteratively tries to satisfy its local constraints". This makes the system highly adaptive, as agents will autonomously react and readjust after deviating from the goal state. Interestingly, this approach aims at reaching stable states (Yu exemplifies it with a self-adjusting bridge) rather than the continuous change found in an ant colony.

Collective robotics draw on the study of social insects. Different design are exploring a variety of characteristics found - or earlier thought to be found - in ants. Especially in early years, however, the multi-robot systems were mostly based on a model of ant behaviour much less dynamic than recent research shows ant colonies really function. In particular, inter-agent communication is rarely utilized to the extent that it occurs in social insects. The fact that networks based on interaction rates are not exploited by the collective robotics community, however, could also stem from the high cost of robots: five or ten robots, as used by Kube and Zhang (1993), would not suffice to create a stable system based on interaction rates.

IV. Conclusion

Social insects accomplish astonishing tasks through self-organization. In the absence of hierarchies and leadership, networks of interactions between individual ants coordinate the emergence of complex behavioural patterns. Researchers in the field of collective robotics have taken much inspiration from the study of social insects, and have attempted to integrate some of their capacities in multi-robot systems. As the study of ants has evolved, new adaptations in collective robotics have become imaginable. But while the paragraph on collective robotics projects is certainly not exhaustive, it shows that some concepts, in particular interaction rate-based networks, which are a powerful example of self-organization, have yet to be transferred to the field of collective robotics.

As Deborah M. Gordon (2010) points out, many multi-robot systems follow a "cybernetic view [in which] each component, whether an ant, a cell in an embryo, or a neuron, has a mission. It accomplishes its mission using the input it gets from various sources", whereas living systems "cause their own development and activity". In particular, ants are not programmed on a particular mission, but as Gordon has shown, change their occupation depending on the circumstances. But as Werfel (2006) points out, collective robotics might in the end not want to recreate social insects completely. Indeed, it seems highly desirable to be able to specify a mission for a multi-robot system to exploit its problem-solving capacities.

Finally, we should not that the link between social insects and (computer) engineering is no uni-directional one. E. O. Wilson, who pioneered modern ant studies, utilized concepts from the burgeoning field of cybernetics for his model of ant behaviour - ideas which at the same time also influenced psychology, fuelling what has become known as the "cognitive revolution". Complex adaptive systems - whether they come in the form of computer networks, ant colonies, or the human brain - share uncanny similarities, and over the time, they have exchanged vocabulary and concepts. Deborah

M. Gordon's emphasis on networks, too, comes at a time when the Internet has brought non-hierarchical organization patterns to the centre of technical and social debates. This may act as a cautionary warning not to blindly accept current research as final truth, but it is also a reminder that crossing disciplinary boundaries can enrich scientific endeavour and inform our understanding of how nature, and we, individually and as a society, interact and make sense of our environment.

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