Evolutionary and Adaptive Systems MSc.

Animal and Machine Intelligence Report

When is many better than one? An examination of co-operative and social animal behaviour and the pros and cons of collective robotics.

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"Many hands make light work."
"Too many cooks spoil the broth."
- English proverbs

Abstract

An examination of the benefits and drawbacks of biologically inspired collective behaviour in robotic systems. The report begins by examining why animals choose to live in groups, explains communication and stigmergy and discusses the difference between co-operative and social behaviour. The second section is concerned with collective robotics; an overview of the field, how lessons from nature can be applied to man-made solutions and a discussion of scale and centralised control. Examples of advantages and disadvantages of collective robotics are given and finally two lists of applications are put forward; one of tasks inherently suited to the collective approach and one of tasks that would benefit from a single-robot solution. In

conclusion it is argued that collective robotics is a useful tool with much potential but one that needs work to progress beyond merely reactive tasks.

Introduction

In recent years a lot of work has been undertaken in the field of biologically-inspired robotics. From Brook's embodied approach **[5]** to machines inspired by cockroaches, crabs and geckos[*] the robotics world is waking up to the fact that there is a lot to learn from nature. The more we examine even the smallest of creatures the more we learn about design, materials, control and efficiency. This change in emphasis has not just been about physical design. Co-operative and social animal behaviours have also been modelled and collective algorithms and robotics are currently areas of active research **[2,9,13]**. This report aims to examine some examples of group behaviour and considers the benefits of applying these ideas to the robotics field.

Inspirational Animals

Why Group Behaviour?

The reason animals live in groups must simply be that to do so brings an advantage to the group or individuals within that group. This advantage could be, for instance, safety, greater spatial capability or combined strength. In the case of the more intelligent animals like dolphins and apes it is reasonable to suppose companionship might be a factor. There is also an evolutionary argument for collective living. Kin selection theory proposes that it is sometimes less beneficial on a cost/benefit basis to reproduce than it is to help relatives (who share some of the same genes) have offspring. This ensures that some of the genes of the individual in question are carried forward in the children of their kin and is put forward as an explanation for altruism in animal groups. It also means there is a reason for living in a group, in that the genepool of the group is not diluted by outside influences.

Let us examine some examples of co-operative and social behaviours in animals:

Co-operative Behaviour

- Termites building nests. These creatures build nests co-operatively using stigmergy **[10]**, that is communication through the environment. Following a set of simple rules they create elaborate structures far beyond the capability of a single insect.

- Ants carrying large prey **[9]**. Ants will co-operate to carry prey far larger than a single ant could manage. If the prey gets stuck the ants will realign and eventually reposition themselves until it is freed. In some instances ants with large mandibles will be called upon to cut the prey into smaller pieces, although co-operative carrying is more efficient in terms of the

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[*] http://www.berkeley.edu/news/media/releases/2002/09/rfull/robots.html

numbers of ants employed. This is presumably because individual ants have to expend more energy balancing the food item.

- Bees finding new nest site. Bees undertake collective decision making when it is time to find a new nest site. Dancing bees communicate several sites, and over a few days one dance emerges as favourite. Soon afterwards the swarm leaves for this site.

- Insect foraging. Bees and ants forage in groups to increase the range and effectiveness of food collection. They also use visual and pheremonal communication to increase the efficiency of the operation.

Social Behaviour

- Herding. Animals that are likely to be preyed upon often form into herds, shoals or flocks. This has two distinct advantages; there are more eyes with which to spot potential danger and, if attacked, the resultant confusion as the herd escapes in different directions can improve each animal's chances of survival. It has been proposed that this behaviour is fundamentally selfish, with members of the herd competing for the safest places in the group **[8]**.

- Pack Hunting. Many predators are solitary hunters but not all. Some, such as wolves and hyenas, hunt in packs and share the spoils. The main reason for this would seem to be that together the pack can bring down much larger prey than one animal could safely take on alone.

- Guard Duty. Prairie dogs live in communal burrows. When foraging one creature will guard against predators by standing on its hind legs to give it a good view across the prairie. Guard duty has to be shared amongst the group which leads to an interesting dilemma, in that guard duty allows others to increase their fitness at the expense of the guard – so why should he or she bother? This problem also occurs in the next example:

- Mutual grooming. Some apes will groom each other to remove parasites and dirt. The interesting question is why an ape will clean another, given that it costs energy to do so and brings no obvious benefit to the cleaner. First of all presumably this procedure will reduce parasitism and disease within the group as a whole so the cleaner benefits indirectly; and secondly the cleaner may at some point require cleaning and will need another ape to help. Thus the behaviour can be caused by prediction of future interactions and is a form of the prisoner's dilemma, a classic co-operation problem **[1]**.

There seems to be a distinction to be drawn between co-operative behaviour and social behaviour in animal groups. All group behaviour results in benefit for those involved; but there are two major differences:

1) Co-operative behaviour, such as that seen in ants and bees, prioritises the survival of the group above that of the individual. Each member of the group has a well defined place within the social structure and this does not usually change. In social behaviour, on the other hand, individuals benefit from living as a group but prioritise themselves. In some cases, such as antelopes herding, group behaviour merely seems to be the best way for the individual to survive predators. In others, such as chimpanzee groups, hierarchies form and are defended; and deception between group members occurs (the latter leading to the 'social brain hypothesis' for the evolution of large brains **[7]**). The position and role of an individual within a group is not fixed and indeed competition for social rank is what seems to drive the more complex behaviours observed.

2) Co-operative behaviour can be seen to be reactionary; the individual's behaviour is directly caused by messages passed on by other members of the group. Some social animals however employ reasoning strategies and are able to solve, and pass on to future generations, problems that would be beyond the capabilities of communal insects. Chimpanzees using sticks to fish for ants is a delightfully pertinent example **[3]**.

Communication and Stigmergy

Animals within a group need to communicate. The famous example of the bees' waggle dance, to recruit other collectors and let them know where a good food source is located, is a good example of direct communication between the members of the group. The distance, direction, and profitability of the food source are all contained within the dance that the bee performs to its fellows. Indirect communication, i.e. communication where the originator is no longer present, is also used. Termites build their mounds, structures that can be 10^5 times as large as an individual termite, using mud balls injected with pheremones. The pheremones in the deposited ball cause nearby termites to add more mud balls in that area. In this way the pile grows, gaining height as the pheremones evaporate at the bottom, until the top eventually joins with another pile to form an arch. This is an example of stigmergy, where "communication is mediated through changes in the environment rather than direct signal transmission" **[10]**. Another example is pheremone trails left between the nest and food source by ants. The pheremones slowly evaporate but each ant adds to the trail, and as the shortest route carries more ants per second, it quickly become established as the path to the food. It is an extraordinarily elegant mechanism, and one which has direct lessons for robotics.

Costs of Group Living

Group living has inherent drawbacks to both the group and the individual. A group will require a lot of food and thus reduce the number of appropriate foraging locations. Any food gained by an individual will have to be shared. Also there may be an optimum size after which adding more individuals is detrimental to the group as a whole. This is obviously true in terms of feeding the group, but is probably true for other tasks as well (for example too many ants clambering over and obstructing each other on a food trail). In social animals, the competition for dominance can cause conflict and loss of group fitness in the short term. Over the long term however the fittest animal should come to dominate (although this raises the question as to the definition of 'fittest' – for instance the smartest animals may not necessarily be the ones best at fighting). Man is unfortunately one of the best examples of this.

Collective Robotics

The State of the Art

Collective robotics, inspired by some of the animals discussed previously, has been a topic of much research in recent years. It has become apparent that through co-operation humble entities can achieve things that far exceed the capabilities of the individual. Various experiments have been carried out with multiple robots including pushing a box too heavy for a single robot to a defined goal **[9]**; resource transport using trail-laying **[12]**; sorting objects into a single pile **[2]** and variable morphology **[13]**. In addition, software agents inspired by co-operative insects have been used to find the quickest route in telecommunications networks, schedule factory tasks and analyse financial data **[4]**. Systems inspired by the trail laying behaviour of ants have been used to solve the classic 'travelling salesman' problem where a salesman must visit a number of towns exactly once by the shortest route. On reflection it is not too much of a surprise that this works, given that it is imperative for ants to find the shortest route to food (both to avoid predation and conserve energy) and have evolved such an efficient system to do so.

Centralised Control

All of the cases mentioned above are remarkable for one thing: there is no centralised control of the group, so the behaviour produced is a result of rules being followed locally by each individual. This is the essence of 'swarm behaviour' and has radically redefined existing thinking about robot control. The benefit of this approach is that each individual only needs limited rules and it is the interaction of the rules that causes the required behaviour; of course this also means the behaviour is not explicitly defined and sometimes the rules can be hard to determine. A good example of this is Craig Reynold's boids **[11]**. Realistic flocking behaviour is created by individual agents following three simple rules:

1. Collision Avoidance: avoid collisions with nearby flockmates
2. Velocity Matching: attempt to match velocity with nearby flockmates
3. Flock Centering: attempt to stay close to nearby flockmates

The important thing to notice here is that nowhere is the nature of flocking or the paths to follow specified; the behaviour results from the interactions of many agents simultaneously applying the same rules.

The Question of Scale

The essential reason for co-operation in a group of animals is that more can be achieved together than apart. Nowhere is this more true than with the social insects, for instance the termite nest example given earlier. In general, then, the smaller the individuals the larger the group will need to be to achieve results, at least at a human scale. This is especially true of nanorobotics, which proposes using enormous numbers of robots approximately 100nm in size to perform exploration, manufacturing and surgical tasks **[6]**. In this case the lessons of co-operative insects are obvious; one robot is virtually useless but many working together can achieve things impossible by any other means. It is in this situation that swarm behaviour becomes vital, as it would be unfeasible to centrally control this number of independent agents.

The main question tackled by this report is when is a group of robots more useful than a single robot of similar cost / weight / total size (or any other relevant comparison). But in this case nanorobots, if ever made a reality, could achieve things that a single large robot could never do, precisely because of their smallness.

Communication Problems

As stated earlier all groups must communicate somehow to combine their efforts, especially if different individuals have different complimentary tasks to carry out. The problem is that as the size of the group increases the number of potential communications increases exponentially and the amount of information being transferred soon becomes unwieldy, especially in the limited bandwidth of human communication systems. The problem of distinguishing the intended recipient of a message increases with each member added and each robot’s complexity, and cost, is increased by the need to be able to encode, transmit, receive and interpret messages in a specific way. Stigmergy is been used to overcome this problem in nature and has been investigated by Holland using collective robots **[2]**. The beauty of this approach is that each robot’s communications overhead does not increase with the size of the group. It merely follows the same fixed set of rules and modifies its behaviour according to messages in its environment. As Holland points out in his paper, stigmergy is very well suited to the control of reactive, behaviour-based robots.

The Pros and Cons of Collective Robotics

Collective robotics is a novel and exciting idea but one that needs careful consideration. The following lists describe some advantages and disadvantages of the approach. It is interesting to note that in some cases a specific feature of the technology is both, as in the control and predictability issues.

Advantages

- Size. Although collective robots could be any size, the nature of lots of small robots interacting can have distinct advantages, such as the ability to access awkward areas, the ability to be difficult to hit with conventional weapons, even the ability to be carried by the wind.

- Resilience. This is one of the main points in favour of large collectives, in that they can still function perfectly if members are lost for any reason.

- No Central Control. Distributed control again makes a collective very resilient to damage.

- Solution-Finding Behaviour. The unpredictability of the interactions between any co-operative robots may lead to the ability to solve problems that were not foreseen or specifically catered for.

- Cost. Once one robot has been designed many can be mass-produced cheaply (perhaps built by nanobots and scheduled by bee-inspired algorithms!). This principle also applies to code development. Robots could also be replaced or repaired much more cheaply.

Disadvantages

- Reduced Capabilities. Smaller robots will have fewer and probably less powerful capabilities than one large robot might incorporate. Shortcomings such as smaller batteries, less elaborate controllers or fewer sensors would have to be compensated for by collective strengths.

- No Central Control. Distributed control systems will be harder to fault-find and maintain.

- Choosing Swarm Rules. From the boids example it is apparent that the rules governing swarm behaviour are not necessarily obvious and the way they interact is crucial. The danger is that as systems increase in complexity the number of rules will increase and their definition may become very difficult.

- Reactive Behaviour. Co-operative robotics is limited to reactive behaviour and does not as yet incorporate reasoning agents.

- Unpredictability. Allowing rules to govern the behaviour of a swarm in a non-direct manner may have unpredicted results.

- Harder to Upgrade. From a practical point of view it will be more work to upgrade the hardware or software of many robots.

Applications

Applications Suited to a Collective Approach

The following lists give some idea of the suitability of the technique to various applications given the points already discussed. Problems that insects solve using this method are obviously very suitable for the collective approach, for instance transport and foraging. However in the same way that co-operative insects are not the only animals to thrive on the earth it is fair to suppose that collective robotics will not solve all problems and that there are some that will require a more traditional approach.

- Transport **[12]**. A collection of robots could be used for transportation, adapting themselves to the size and nature of the task and calling in reinforcements if needed.

- Search. The increased spatial potential of a swarm makes it very useful for search and rescue scenarios. This is especially true as robots can be sent into situations too dangerous for people to attempt, and distributed control means that some individuals can be lost with little overall negative effect.

- Imaging. If each robot in a swarm has a camera an area could quickly be mapped.

- Exploration. For the reasons given above mobile groups of robots would be very useful in exploration of new planets. In this case a hybrid robot can be imagined, with a central lander containing a powerful transmitter acting as ‘base’ to a group of data-collecting rovers who return when their batteries are running low to recharge and transfer collected information.

- Sorting and Tidying **[2]**. Based on the nest cleaning of ants, a group of robots could use stigmergy to collect waste into a single pile for later collection.

- Mine Clearance. The relative low cost and resilience of collective robots make them a good choice for mine clearing duties.

- Poly-Morphology **[13]**. Robots that can join together in different formations can be used to create a single robot with variable shape. This means the robot could assume different morphology for travelling on smooth or rough ground, or climbing stairs or a wall as appropriate and then split into component parts to perform a search or reconnaissance.

- Military. This technology obviously has a lot of military applications. Search and rescue can easily be modified to search and destroy, and a group of small robots will be far harder to hit with conventional weapons than one large one.

Applications Suited to a Single Robot

- Large Run Time. If a robot has to run continuously for a long time large robots have the edge as they can carry larger batteries and support more solar cells or other power generating mechanisms.

- Reasoning-Based Tasks. Collective robotics as described in this report relies on relatively dumb, reactive agents achieving results through simple rule-based interaction. As Brooks has shown reactive behaviour is fine for locomotion but more complex problems will require a reasoning approach beyond this.

- Maximum Strength or Power. Large robots built for the same cost as a collection of small ones will be able to utilise more powerful and larger actuators.

- Better Sensing. The larger controller possible in a single robot will be able to process more information from more sensors.

Conclusion

Collective and co-operative engineering is a wonderful idea; it is efficient, practical, resilient and indeed sometimes the only possible approach. However it is currently only suited to particular reactive applications where the strengths of working collectively outweigh the weakness of the individual members. One has to ask whether collective decision-making will scale up to tasks that involve true reasoning and cognition. Will the group work as a democracy, each voting for the solution that it deems correct, or will there be a hierarchy or dictatorship where the group has rulers and a social structure? From the natural world it is clear that the more advanced animals capable of reasoning are not constrained by having to live co-operatively, and indeed the freedom gained by not being a cog in a larger machine might be the reason for the greater achievements of these creatures. Collective robotics has enormous potential, but will never progress beyond specific, useful but ultimately limited applications unless the ants can figure out how to fish for chimpanzees.

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