Swarm Robotics: Nature Inspired Systems

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Abstract— Swarm robotics is a developing field offering vast scope for research and formulating specialized applications. Modeled on the behavior of natural swarms in the environment, swarm robotics aims to capitalize on the great potential that decentralized swarm systems consisting of a large number of relatively simple units offer. This paper introduces major aspects of swarm robotics with majority focus on analyzing coordinated actions of natural colonies to help define and understand the characteristics, principles of operation and modeling techniques used to configure and operate swarm robotic systems. The distinctive benefits of swarm systems, which heavily rely on effective localized information exchange and coordination has been discussed along with the immense potential that the field of swarm robotics offers, if properly exploited.

Keywords— Information exchange, stigmergy, coordinated behavior, self-organization, decentralized operation, natural colonies, cooperative control, autonomy.

1. INTRODUCTION

Swarm robotics deals with the coordination and integration of large groups of simplistic robots that are controlled using local means. The swarm bot comprises of many small robots, which are autonomous and portable. These robots can either be independent or self-assemble into a swarm formation. With the help of these small robots, the costs are lowered and the system is much more stable and robust as the interaction is local and the probability of error for individual robots is minimized. The individual robots aren’t sentient enough to carry out heavy tasks on their own but can do so, when they are in a swarm by distributing the labor and coordinating within themselves. These swarms are self-adaptable, self-organized and decentralized. The inspiration behind swarm robotics came from nature itself. Large societies of insects could carry out insurmountable tasks, which couldn’t have been possible if they worked alone. The potential applications of swarm robotics are tasks that can be miniaturized, require cheap designs or tasks that are executed on a large scale and are dangerous to humans and robots such as disaster relief, search operations or military applications.

2. INSPIRATION FROM NATURE SWARMS

Nature based swarms have been the inspiration behind most of the foundational research on swarm robotics. The behavior of social anthropoids, birds or fishes, as a collective functioning unit and their intra-organizational interactions have demonstrated noteworthy features such as effective division of labor, great flexibility, path planning, robustness and so on. Although the individual members of these swarms, which may largely vary in size from a group of ten to millions, may not possess great intelligence or capabilities, the group as a whole demonstrates superlative degrees of performance, accomplishing complex tasks such as large distance migration, foraging for food, nest building etc. This is achieved by effective information exchange and coordination among the individuals. Some of the most recent examples found in nature are discussed below:

2.1. ANT AND BEE COLONIES

Ants use pheromone, tactile sensations and sound as means of information exchange. They leave behind pheromone trails along a route towards food resources, in the environment. The best path is identified when other ants successively pick up these trails along the shortest routes thereby strengthening the decision to follow these better routes.

2.2. BIRD CROWDS

It observed that birds arrange themselves into unique formations during migration. This pattern formation is not merely coincidental but indeed a deliberate action, which helps birds to accurately navigate across hundreds of miles to their desired location. They employ inputs from a variety of factors such as magnetic fields, sun compass, time estimation, and visual landmarks, to aid in the above process.

2.3. BACTERIA COLONIES

Bacteria operate as biofilms that are simply multi-cellular clusters with individual cells communicating via inter-cell signals. Such cooperative functioning allows for a division of labor at cellular level, improving resource access abilities, increasing resistance to deterrents, thus benefitting at a global level and vastly increasing survival chances of the aggregate bacteria communities.

2.4 FISH SCHOOLS

Fish usually live in a group known as fish schools that continuously organize themselves in a specific shape that facilitates rapid and smooth, upstream-downstream locomotion, by effectively avoiding collisions with neighboring fish schools with the help of "schooling marks" on their shoulders. This helps them in efficient movement, safeguarding against predators and also in foraging.

Above mechanisms are not just impressive on their own but offer immense potential if properly implemented in robotic systems.

3. CHARACTERISTICS OF SWARM ROBOTICS

3.1. PARALLEL

A swarm can have a large population size, which helps in dealing with multiple targets at once. These targets can be spread over a wide range in the environment hence the search time for swarm is reduced significantly.

3.2. SCALABLE

The swarm is localized, which enables the individuals to join or quit at whim without disrupting the whole swarm. The swarm is adaptable to change in size because of the task reallocation strategies. They are adaptable to different sizes of the population without modifying the software or hardware, which renders them very useful in real-time applications.

3.3. STABLE

The swarm is not affected majorly even if a part of the swarm quits due to exigent circumstances. The swarm remains functional but the performance might get affected due to fewer robots. In dangerous environments, this is an important asset.

3.4. ECONOMICAL

Cost of swarm is significantly low in terms of designing, manufacturing and maintenance. Individual units can be massively manufactured while a single robot needs precise manufacturing.

3.5. ENERGY EFFICIENT

Individual units are smaller and simpler as compared to a single robot, which reduces the energy cost and consumption. This helps in improving the lifetime of swarm.

3.6. AUTONOMY

Individual units are autonomous and capable of exercising control by interacting and motioning in environment. They don't need to be given commands externally.

3.7. DECENTRALIZATION

With help of predetermined rules, individuals can complete tasks without centralized controls. This guarantees scalability and flexibility of swarm.

3.8. HOMOGENOUS

Division of roles amongst individuals must be small and the number of robots for each role must be large. These roles indicate physical structure of robots and shouldn't be changed during tasks.

3.9. FLEXIBILITY

If swarm has high flexibility, it can deal with different tasks using the same hardware and implementing minor changes to the software. This is helpful in foraging techniques, searching or flocking. With help of machine learning, robots can learn from past behavior and modify their strategy accordingly.

4. PRINCIPLES OF OPERATION

Swarm robotics is primarily based on the principles of swarm intelligence which are heavily borrowed and in fact derived from the collective behavior of social insects such as ants, honey bees, wasps, termites and so on. Scientific studies have shown that, a social insect colony consists of autonomous units distributed in the environment and functioning in a decentralized manner. These insects or units are not equipped to assess a global scheme or to centralize information about the state of its entire colony but in fact interact with each other and the environment based on local information that is without knowledge of the global work pattern. Each insect or unit simply follows a small set of behavioral rules. This behavior can be broken down into following two primary principles of swarm intelligence:

4.1. STIGMERGY

It entails a mechanism of indirect co-ordination between the colony units or their actions through the environment. The local environment serves as a work state memory by storing traces left by an agent's actions, which provide a stimulus for subsequent actions thereby eliciting a behavioral response from itself or other units of the swarm or colony. This principle can be best understood by studying nest building in social wasps. Building activities are governed by the local configuration of cells detected by the wasps on the nest. They sense the local configurations of cells on the outer periphery of the comb with their antennae and use this information to decide where to build a new cell. Indeed, the architecture by itself provides enough data and constraints to ensure the coordination of the wasp building activity. Potential building sites on the comb differ in probability to be chosen by wasps when they start to build a new cell. Wasps have a higher probability to add new cells to a corner area with three existing adjacent walls as against starting a new row, by expanding on the side of an existing row. Such behavior helps the individual agents to make decisions, simply by relying on localized information from their immediate work area or environment.

4.2. SELF ORGANIZATION

Self-organization is a set of dynamical mechanisms, which produce intelligent structures at the global level of a system from interactions among its lower level, autonomously functioning units that are not explicitly programmed at the individual level. It is based on four essential components:

4.2.1. POSITIVE FEEDBACK RESULTING IN ACTIVITY AMPLIFICATION

This can be understood by understanding how a decision is made by a colony of ants in choosing between a short path and a long path leading to a food source. Using the trail, the shortest branch is selected in most cases. Initially both paths are given equal preference by the first ants to reach the food source. The ones that take the shortest path reach the nest first and thus in accordance with the trail-laying trail-following behavior the shorter route gets more prominently marked with pheromone thereby attracting the ants that wish to traverse from the nest to the food source. Thus here, the positive feedback amplifies an initial difference induced by the path geometry making it easy to make a choice between the two without the need of complex decision making algorithms or programming, eventually establishing a trail network at the global level.

4.2.2. NEGATIVE FEEDBACK FOR ACTIVITY BALANCING OR STABILIZATION BY COMPENSATING FOR THE POSITIVE FEEDBACK

Continuing with the above example of food foraging among ants we can categorize the following factors as contributors of a negative feedback. Insufficient number of available foraging agents, exhaustion of food source, and the disappearance of pheromone trail on account of evaporation or a competition between alternative paths to attract foragers.

4.2.3. AMPLIFICATION OF RANDOM FLUCTUATIONS BY POSITIVE FEEDBACKS

Amplifying random fluctuations is essential to the growth of swarm colonies as these random behaviors followed by various insect groups, which are often described as stochastic behavior or actions, often help to engender new global structures. Moreover the importance of randomness can be gauged by the fact that it helps to engage the colony in finding newer or maybe better solutions to existing tasks and problems. Consider an instance where misguided or lost foragers can discover unexploited food sources, and then recruit nest mates to these food sources.

4.2.4. MULTIPLE INTERACTIONS

Irrespective of being direct or stigmergic in nature, multiple interactions among independent units of a swarm are essential to generate deterministic outcomes and for producing large and sustainable structures. The whole foundation of a swarm colony ceases to exist if the individual units do not interact and hence exchange information among themselves and the environment.

5. MODELING SWARM ROBOTS

5.1. GENERAL MODELING

The swarm robotics model is essential for executing the coordination algorithms for monitoring the behavior and communication patterns of individual units. These robots have rudimentary functions like sensing, interacting and motioning. The model is divided into 3 modules depending on the functions they wish to accomplish: information exchange, basic and advanced behavior.

5.1.1. INFORMATION EXCHANGE MODULE

This is the crux of swarm robotics as it enables cooperation between robots and helps control the swarm. It has two main functions: limited sensing and local communication. Information exchange can occur in 2 ways: interaction with robots or the environment. In nature, we can have examples of direct interaction via tentacles, voice or gesture. Indirect interaction, though, is much more subtle. In this, the individuals sense the message in the environment, react to it and send back the message in the environment. Pheromones are one example of this. There are three ways of sharing information:

5.1.1.1. Direct communication: similar to wireless networks.

5.1.1.2. Communication through environment: the environment acts as the medium for interaction and is also known as stigmergy.

5.1.1.3. Sensing: Individuals can sense the robots and the environment with help of sensors. It can be helpful in obstacle avoidance, target search, etc.

5.1.2. BASIC BEHAVIOR MODULE

Its individuals have functions such as motioning and local planning. These set swarm robotics apart from multi agent systems and sensor networks systems. It is based on input from communicating and sensing that help the robots to compute their desired movements.

5.1.3. ADVANCED BEHAVIOR MODULE

Robots in complex swarms have additional functions such as task decomposition, allocation and adaptive learning. Task decomposition and allocation help in improving the efficiency of swarm and adaptive learning enhances adaptability of the swarm in different environments.

5.2. MODELING METHODS FOR SWARM ROBOTICS

Modeling helps to conform the swarm robotic algorithm to be scalable for hundreds of thousands of robots.

5.2.1. SENSOR-BASED MODELING

The sensors and actuators form the main components of the system along with the other objects in the environment.

5.2.2. MICROSCOPIC MODELING

Robots and interactions are modeled as finite state systems. Behavior of each unit is defined as many states and transfer condition is based on input from communication and sensing.

5.2.3. MACROSCOPIC MODELING

It is opposite of microscopic modeling. System behaves as a differential equation and the system state is the average number of robots for a particular state at some time step.

5.2.4. MODELING FROM SWARM INTELLIGENCE ALGORITHMS

These are cooperative schemes from swarm intelligence algorithms that are implemented by swarm robotics. Most common example is the particle swarm optimization (PSO). PSO imitates the flocking of birds. Another example is that of ant colonies. These inspirations provide efficient heuristics for searching and routing in a dynamic environment.

6. COOPERATION SCHEMES BETWEEN ROBOTS

Cooperation is an essential element of a swarm robotics model since the system primarily functions due to coordinated or synchronized interactions between the lower-level autonomous units. In fact coordination is considered as an advanced behavior in the swarm robotics modeling. Cooperation occurs at two levels: individual level and swarm level in swarm robotics. Individual level coordination correlates and synchronizes the responses of the swarm agents and their learning and adaptive behaviors with stimuli from environment and is imperative to yield useful actions out of individual agents. Swarm level coordination integrates the former cooperation, to yield the typical collective tasks such as gather, disperse or formation.

Following are few schemes describing coordination that focus on the physical layer of the robots.

6.1. SWARM ARCHITECTURE

The architecture of the swarm forms a basis or skeleton for robotic activities and interactions between agents. Most importantly it helps define the topology for communication and local exchange of information among robots. The architecture of swarm thus largely affects the co-ordination based swarm performance. Hence it is imperative to select the architecture with careful consideration of several factors such as the scale of operation, frequency and complexity of interactions and cooperation among the robots.

6.2. DETERMINING LOCATIONS

Individual swarm units function without a centralized governing system and hence are entirely self-reliant in identifying, differentiating and locating neighboring robots in their domain of function. The absence of a global coordinating system needs to be countered by making available a method for locating other robots within stipulated time. This is realized using on board sensors and filters, which can sense and distinguish between different sound and light waves across the spectrum. While absolute positioning can be applied in some cases it is more important to establish a relative positioning mechanism since robots have limited abilities and localized functioning without a central supervised control. Thus employing a relative positioning algorithm can only ensure coordination.

6.3. PHYSICAL LINKS

Physical connections need to be used in certain situations, which cannot be dealt with by a single robotic agent. These may include coordinated transportation or crossing over large gaps. In these cases, the robots should interact, exchange relevant information and dock before they continue to execute their actions. Several types of physical associations using sensors and actuators for surpassing gaps and difficult terrains have been developed along with infrared ray based localizing and docking methods.

6.4. SELF-ORGANIZATION AND SELF-ASSEMBLY

Self-organization involves local interactions of the lower level units to result in a global structure. The actions of basic units or robots are not supervised or controlled by a centralized monitoring program. A robot establishes communication with the other robots through the already built structures i.e. the interactions and responses of robots are mentored by the process of building. One can study such schemes by simply observing colony insects like ant or bees building their nests. Either discrete or continuous interaction is employed by ants to communicate with environment during the nest building process. While discrete interaction responds to the type of stimulation, the continuous interaction gives a response corresponding to the size of stimulation. Self-assembly describes the ability of few swarm system's to organize themselves from individual units into intended configurations without human aid.

7. FUTURE SCOPE

The swarms as a whole can carry out jobs that can provide new avenues to humans for harnessing power of machines. Ability of controlling swarms can have wide applications from medicine to military. They can be used in military, search and rescue operations, or in areas that can be dangerous for humans. They can also be used in industrial applications for improving manufacturing processes and ensuring workplace safety. The upcoming technologies in this are the bionic aero vehicles, which are inspired by swarm intelligence, machine bees or cockroaches with surveillance equipment, which can be used in future defense operations.

8. CONCLUSION

Swarm robotics is an upcoming research field that draws inspiration from swarm intelligence and robotics. Along with cooperation algorithms that enable control for swarm, manufacturing is imperative for developing swarm robotic systems. With the advent of Micro Electro Mechanical technology in terms of the actuators, sensors and electronic components; size and cost of robots has reduced substantially. Further progress in hardware technology and cooperative algorithms in swarm intelligence and nature will go a long way in boosting the development of swarm robotic systems.

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