Swarm Intelligence

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Studies on Swarm Intelligence are developed from the discoveries and researches of collective behaviors emerged from the social animals or insect group. More than fifty years ago, biologists have reported that a new kind of intelligence form can emerge from some social insects, fish, birds, and mammals. For example, African termites (*Macrotermes bellicosus*) can build nest that may reach a diameter of thirty meters and a height of six meters with complex internal structure (Grasse 1984). These skyscrapers are built by millions of tiny (1–2 mm long) and completely blind individuals. Apparently, in terms of cognitive or communicational abilities, the complexity of an individual termite is not intelligent enough for designing and generating such complex system. Another example of collective behavior is the food recruitment in ant colony. At the beginning of the 1990s, Jean-Louis Deneubourg and his collaborators (Deneubourg, Goss et al. 1991) found there is a high probability for a colony of ants to find out the shortest path from multiple paths between the food source site and the nest. Many more examples of the impressive capabilities in other biological systems, such as colonies of bacteria or amoeba, fish schools, bird flocks, and sheep herds, share similar collective properties. However, it is hard to explain the complexity of all the behaviors at the colony scale level if only considering individuals of the colony. For a long time, these kinds of collective behaviors emerged from social insects or animal society have remained mysterious and thing happens as if an “invisible hand” or leader inside the colony coordinates the individuals’ activities. The power of the collective behavior of social insects has also inspired novelists. Michel Crichton, in his novel "Prey", describes a swarm of nanorobots that can generate complex intelligence using their collective mind. Early attempt to explain this collective behavior phenomenal focused on building the connection between the observed complex behavior in the colony level and the behavior of individual. It was believed that the complex swarm behaviors can only be generated by the individuals with complex cognitive capability. In the research of the social insect behaviors, the queen of an insect colony used to be considered as the leader of the colony and have the capability of collecting the colony’s global information, supervising the worker’s works, and coordinating the behaviors of the whole colony. However, researches indicate that neither queen nor workers have the neuron capability for collecting colony global information, processing the information and making decision on controlling the behaviors of the whole colony.

The first serious theoretical explanation of the emerging of collective behaviors in social insects was provided by French biologist Pierre-Paul Grasse. In 1950, Grasse introduced the concept of stigmergy in conjunction with his research on termites. His study has shown that a particular configuration of a termite colony’s environment could trigger a termite to modify its environment, for example, dropping a mud in a particular place to build or maintain the nest. The modification in turn stimulates the original or other termites in colony to further transform its environment. Grasse made a general definition of stigmergy as: “the stimulation of the workers by the very performances they have achieved”. The concept of stigmergy provides a theory for explaining how distributed, ad hoc contributions from individuals could lead to the emergence of large collaborative enterprises.

In recent years, some computer scientists adopt the stigmergy model to solve complex problems and categorized it as Swarm Intelligence. Swarm Intelligence is an artificial intelligence technique involving studies of collective behaviors in decentralized systems. Beni and Wang (Beni and Wang 1991) first introduced the term of Swarm Intelligence in the context of cellular robotic systems. Bonabeau (Bonabeau, Henaux et al. 1998; Bonabeau, Dorigo et al. 1999) extended the concept of Swarm Intelligence to the work involved with algorithm design or distributed problem-solving devices. He defined the Swarm Intelligence as “any attempt to design

algorithms or distributed problem-solving devices inspired by the collective behavior of social insect colonies and other animal societies". The major concepts underlying Swarm Intelligence includes decentralization, stigmergy, self-organization, emergence, positive and negative feedbacks. Currently, most popular research directions in Swarm Intelligence are grounded on the following three research areas: Flocking model (Reynolds 1987), Ant Colony Optimization (ACO) (Bonabeau, Dorigo et al. 1999) and Particle Swarm Optimization (PSO) (Eberhart and Kennedy 1995).

Flocking model, first proposed by Craig Reynolds (Reynolds 1987), is a bio-inspired computational model for simulating the animation of a flock of entities called "boid". It represents group movement as seen in bird flocks and schools of fish in nature. In this model, each boid reacts to the neighboring mates in the flock and the environment it can sense and makes its own decisions on its movement according to a small number of simple steering rules. Three simple steering rules need to be executed at each instance over time. Three basic rules include: (1) Separation: Steering to avoid collision with other boids nearby; (2) Alignment: Steering toward the average heading and match the velocity of the neighbor flock mates; (3) Cohesion: Steering to the average position of the neighbor flock mates. By following these three simple rules, boids in the simulation can quickly form a stable swarm formation, in which every boid has the minimum distance from every other boid and will not move any further than the maximum distance.

The Ant Colony Optimization (ACO) is a heuristic algorithm that is inspired by the food foraging behavior of ants. Marco Dorigo introduced the first ACO system in his Ph.D. thesis (1992). The idea underlying the ACO algorithm is to mimic the ant's foraging behavior with "simulated ants" moving around a graph searching for the optimal solution. As ants forage, they deposit a trail of slowly evaporating pheromone. All foraging ants use the pheromone as a guide regardless of whether the pheromone is deposited by itself or other ants. Pheromones accumulate when multiple ants travel through the same path. The pheromones on the tail evaporate as well. If an ant reaches the food first and returns to the nest before others, its return trail's pheromone is stronger than other trails on which ants have not found food or have longer distances from the food source because the return trail has been traveled twice. This high volume of pheromone volume attracts other ants to follow this trail. The more the trail is traveled, the stronger the pheromone content on this trail will be. The level of pheromone on other less traveled trails will decrease since fewer ants travel those trails and the pheromone evaporates. Eventually, the trail with highest level of pheromone and traveled by most of foraging ants will be the shortest tail between food sources and nest.

Particle Swarm Optimization (PSO) is a population-based stochastic optimization technique that can be used to find an optimal, or near optimal, solution to a numerical and qualitative problem. Inspired by the social behavior of flocking birds or a school of fish, Eberhart and Kennedy originally developed the PSO in 1995 (Eberhart and Kennedy 1995). In PSO, birds in a flock are symbolically represented as particles. These particles can be considered as simple agents "flying" through a problem space. A problem space in PSO may have as many dimensions as needed to model the problem space. A particle's location in the multi-dimensional problem space represents one solution for the problem. When a particle moves to another location, a new solution is generated. This solution is evaluated by a fitness function that provides a quantitative value of the solution's utility. The velocity and direction of each particle moving along each dimension of the problem space are altered at each generation of movement. It is the particle's personal experience combined with its neighbors' experience influences the movement of each particle through a problem space.

Swarm intelligence is a growing research field for solving distributed problems. It offers an alternative way to design system that has traditionally required centralized control and extensive preprogramming. However, because the pathways to solutions are not predefined but emergent, there is no general guideline on how to design a swarm intelligent system. The system designer has to rely on trial and error process to determine how the agents of a swarm-based

solution should be programmed. Currently, most of the swarm intelligence studies and applications are mimicking the collective behaviors of social insect or animal society. These swarm intelligence applications seek to solve tasks strictly relying on simple individual capabilities, local interaction mechanisms and indirect communication (stigmergy). Adaptation, computational intelligence, cognition and other sophisticated capability are absent at the individual level in current swarm intelligence system.

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KEY TERMS AND THEIR DEFINITIONS

Swarm Intelligence:

Swarm intelligence is an emerging field of biologically-inspired artificial intelligence based on the collective behavior model of social insect colonies and other animal societies.

Flocking Model:

The Flocking Model is a bio-inspired computational model for simulating the animation of a flock of entities. The Flocking model was first proposed by Craig Reynolds in 1987.

Particle Swarm Optimization:

The Particle Swarm Optimization (PSO) is a population based stochastic optimization technique that can be used to find an optimal, or near optimal, solution to a numerical and qualitative problem. PSO was originally developed by Eberhart and Kennedy in 1995, inspired by the social behavior of flocking birds or a school of fish.

Ant Colony Optimization:

The Ant Colony Optimization (ACO) is a heuristic algorithm that is inspired from the food foraging behavior of ants. Dorigo introduced the first ACO system in his Ph.D. thesis in 1992.