Swarm intelligence

Swarm intelligence (SI) is the collective behaviour of decentralized, self-organized systems, natural or artificial. The concept is employed in work on artificial intelligence. The expression was introduced by Gerardo Beni and Jing Wang in 1989, in the context of cellular robotic systems.[1]

SI systems are typically made up of a population of simple agents or boids interacting locally with one another and with their environment. The agents follow very simple rules, and although there is no centralized control structure dictating how individual agents should behave, local, and to a certain degree random, interactions between such agents lead to the emergence of "intelligent" global behavior, unknown to the individual agents. Natural examples of SI include ant colonies, bird flocking, animal herding, bacterial growth, and fish schooling.

The application of swarm principles to robots is called swarm robotics, while 'swarm intelligence' refers to the more general set of algorithms. 'Swarm prediction' has been used in the context of forecasting problems.

Example algorithms

Ant colony optimization

Ant colony optimization (ACO) is a class of optimization algorithms modeled on the actions of an ant colony. ACO methods are useful in problems that need to find paths to goals. Artificial 'ants'—simulation agents—locate optimal solutions by moving through a parameter space representing all possible solutions. Real ants lay down pheromones directing each other to resources while exploring their environment. The simulated 'ants' similarly record their positions and the quality of their solutions, so that in later simulation iterations more ants locate better solutions.[2]

One variation on this approach is the bees algorithm, which is more analogous to the foraging patterns of the honey bee.

River formation dynamics

River formation dynamics (RFD)[3] is an heuristic method similar to ant colony optimization (ACO). In fact, RFD can be seen as a gradient version of ACO, based on copying how water forms rivers by eroding the ground and depositing sediments. As water transforms the environment, altitudes of places are dynamically modified, and decreasing gradients are constructed. The gradients are followed by subsequent drops to create new gradients, reinforcing the best ones. By doing so, good solutions are given in the form of decreasing altitudes. This method has been applied to solve different NP-complete problems (for example, the problems of finding a minimum distances tree and finding a minimum spanning tree in a variable-cost graph[4]). The gradient orientation of RFD makes it specially suitable for solving these problems and provides a good tradeoff between finding good results and not spending much computational time. In fact, RFD fits particularly well for problems consisting in forming a kind of covering tree.[5]

Particle swarm optimization

Particle swarm optimization (PSO) is a global optimization algorithm for dealing with problems in which a best solution can be represented as a point or surface in an n-dimensional space. Hypotheses are plotted in this space and seeded with an initial velocity, as well as a communication channel between the particles.[6][7] Particles then move through the solution space, and are evaluated according to some fitness criterion after each timestep. Over time, particles are accelerated towards those particles within their communication grouping which have better fitness values. The main advantage of such an approach over other global minimization strategies such as simulated annealing is that the large number of members that make up the particle swarm make the technique impressively resilient to the problem of local minima.
Stochastic diffusion search
Stochastic diffusion search (SDS) is an agent-based probabilistic global search and optimization technique best suited to problems where the objective function can be decomposed into multiple independent partial-functions. Each agent maintains a hypothesis which is iteratively tested by evaluating a randomly selected partial objective function parameterised by the agent's current hypothesis. In the standard version of SDS such partial function evaluations are binary, resulting in each agent becoming active or inactive. Information on hypotheses is diffused across the population via inter-agent communication. Unlike the stigmergic communication used in ACO, in SDS agents communicate hypotheses via a one-to-one communication strategy analogous to the tandem running procedure observed in some species of ant. A positive feedback mechanism ensures that, over time, a population of agents stabilise around the global-best solution. SDS is both an efficient and robust search and optimisation algorithm, which has been extensively mathematically described.

Gravitational search algorithm
Gravitational search algorithm (GSA) is constructed based on the law of gravity and the notion of mass interactions. The GSA algorithm uses the theory of Newtonian physics and its searcher agents are the collection of masses. In GSA, we have an isolated system of masses. Using the gravitational force, every mass in the system can see the situation of other masses. The gravitational force is therefore a way of transferring information between different masses(Rashedi, Nezamabadi-pour and Saryazdi 2009)[8]. In GSA, agents are considered as objects and their performance is measured by their masses. All these objects attract each other by a gravity force, and this force causes a movement of all objects globally towards the objects with heavier masses. The heavy masses correspond to good solutions of the problem. The position of the agent corresponds to a solution of the problem, and its mass is determined using a fitness function. By lapse of time, masses are attracted by the heaviest mass. We hope that this mass would present an optimum solution in the search space. The GSA could be considered as an isolated system of masses. It is like a small artificial world of masses obeying the Newtonian laws of gravitation and motion (Rashedi, Nezamabadi-pour and Saryazdi 2009).

Intelligent Water Drops
Intelligent Water Drops algorithm (IWD) is a swarm-based nature-inspired optimization algorithm, which has been inspired from natural rivers and how they find almost optimal paths to their destination. These near optimal or optimal paths follow from actions and reactions occurring among the water drops and the water drops with their riverbeds. In the IWD algorithm, several artificial water drops cooperate to change their environment in such a way that the optimal path is revealed as the one with the lowest soil on its links. The solutions are incrementally constructed by the IWD algorithm. Consequently, the IWD algorithm [9] is generally a constructive population-based optimization algorithm.

Charged System Search
Charged System Search (CSS) [10] is a new optimization algorithm based on some principles from physics and mechanics. CSS utilizes the governing laws of Coulomb and Gauss from electrostatics and the Newtonian laws of mechanics. CSS is a multi-agent approach in which each agent is a Charged Particle (CP). CPs can affect each other based on their fitness values and their separation distances. The quantity of the resultant force is determined by using the electrostatics laws and the quality of the movement is determined using Newtonian mechanics laws. CSS is applicable to all optimization fields; especially it is suitable for non-smooth or non-convex domains. This algorithm provides a good balance between the exploration and the exploitation paradigms of the algorithm which can considerably improve the efficiency of the algorithm and therefore the CSS also can be considered as a good global and local optimizer simultaneously.


Applications

Swarm Intelligence-based techniques can be used in a number of applications. The U.S. military is investigating swarm techniques for controlling unmanned vehicles. The European Space Agency is thinking about an orbital swarm for self assembly and interferometry. NASA is investigating the use of swarm technology for planetary mapping. A 1992 paper by M. Anthony Lewis and George A. Bekey[11] discusses the possibility of using swarm intelligence to control nanobots within the body for the purpose of killing cancer tumors.

Crowd simulation

Artists are using swarm technology as a means of creating complex interactive systems or simulating crowds. Stanley and Stella in: Breaking the Ice was the first movie to make use of swarm technology for rendering, realistically depicting the movements of groups of fish and birds using the Boids system. Tim Burton's Batman Returns also made use of swarm technology for showing the movements of a group of bats. The Lord of the Rings film trilogy made use of similar technology, known as Massive, during battle scenes. Swarm technology is particularly attractive because it is cheap, robust, and simple.

Airlines have used swarm theory to simulate passengers boarding a plane. Southwest Airlines researcher Douglas A. Lawson used an ant-based computer simulation employing only six interaction rules to evaluate boarding times using various boarding methods.(Miller, 2010, xii-xvii)[12]

Ant-based routing

The use of Swarm Intelligence in Telecommunication Networks has also been researched, in the form of Ant Based Routing. This was pioneered separately by Dorigo et al. and Hewlett Packard in the mid-1990s, with a number of variations since. Basically this uses a probabilistic routing table rewarding/reinforcing the route successfully traversed by each "ant" (a small control packet) which flood the network. Reinforcement of the route in the forwards, reverse direction and both simultaneously have been researched: backwards reinforcement requires a symmetric network and couples the two directions together; forwards reinforcement rewards a route before the outcome is known (but then you pay for the cinema before you know how good the film is). As the system behaves stochastically and is therefore lacking repeatability, there are large hurdles to commercial deployment. Mobile media and new technologies have the potential to change the threshold for collective action due to swarm intelligence (Rheingold: 2002, P175).

Airlines have also used ant-based routing in assigning aircraft arrivals to airport gates. At Southwest Airlines a software program uses swarm theory, or swarm intelligence—the idea that a colony of ants works better than one alone. Each pilot acts like an ant searching for the best airport gate. "The pilot learns from his experience what's the best for him, and it turns out that that's the best solution for the airline," Dr. Douglas A. Lawson explains. As a result, the "colony" of pilots always go to gates they can arrive and depart quickly. The program can even alert a pilot of plane back-ups before they happen. "We can anticipate that it's going to happen, so we'll have a gate available," Dr. Lawson says.[13]
References in popular culture

Swarm intelligence-related concepts and references can be found throughout popular culture, frequently as some form of collective intelligence or group mind involving far more agents than used in current applications.

- A popular Soviet SF writer Sever Gansovsky in his short story “The Host of Bay” (1962) described a sea monster consisting of microscopical particles which can self-organize themselves into a unity for hunt.
- *Talus*[^14] by Erol Ozan deals with an exotic life form powered by swarm intelligence emerging from the telepathic minds of kalonoro, Madagascar's cryptic hominids.
- The Borg in Star Trek
- In *28 Days Later*, the Infected have some form of hive mind, in that they have some form of intelligence which enables them to hunt down and kill the survivors of the Rage Virus. This "intelligence" is shown mainly when the Infected attack in large packs, as they focus all their attention on the human survivors, and will not stop until the survivors are dead or Infected.
- The Zerg of the Starcraft universe demonstrate such concepts when in groups and enhanced by the psychic control of taskmaster breeds; the Zerg's original leader, the Overmind, was generally thought of not as an individual with a central intelligence to control others but instead as a being which embodies the hive mind of Zerg that are mentally linked
- Science fiction writer Olaf Stapledon may have been the first to discuss swarm intelligences equal or superior to humanity. In *Last and First Men* (1931), a swarm intelligence from Mars consists of tiny individual cells that communicate with each other by radio waves; in Star Maker (1937) swarm intelligences founded numerous civilizations, composed of flocks of birds or, as the universe cools, energy-efficient swarms of burrowing slugs; ultimately all intelligence in the universe swarms into a single entity barely capable of perceiving the Supreme Moment.
- *Decipher* by Stel Pavlou deal with the swarm intelligence of nanobots that guard against intruders in Atlantis.
- *Prey*, by Michael Crichton deals with the danger of nanobots escaping from human control and developing a swarm intelligence.
- *Wyrm*, a novel by Mark Fabi deals with a virus developing emergent intelligence on the Internet
- *Swarm*, a short story by Bruce Sterling about a mission undertaken by a faction of humans, to understand and exploit a space-faring swarm intelligence.
- The Hacker and the Ants, a book by Rudy Rucker on AI ants within a virtual environment
- *Allucination*, a short story by Isaac Asimov about an alien insect-like swarm, capable of organization and provided with a sort of swarm intelligence.
- *The Invincible* science fiction novel by Stanislaw Lem where a human spaceship finds an intelligent behavior in a flock of small particles that were able to defend themselves against what they found as a menace.
- In The Matrix movies, the robotic sentinels exhibit signs of swarm intelligence. Additionally, in *The Matrix Revolutions*, a machine called the Deus Ex Machina uses a swarm of thousands of insect-like robots to form a giant animated face.
- In the anime, *Soukou no Strain*, unmanned robotic drones known as TUMORS display signs of swarm intelligence as they attack in groups.
- In the dramatic novel and subsequent mini-series: "The Andromeda Strain" by author Michael Crichton, A virus from the future communicates between individual cells and displays the ability to think and react individually and as a whole, and as such displays a semblance of "swarm intelligence".
- In the computer RPG Planescape: Torment, the protagonist encounters monsters called cranium rats, which grow more intelligent in larger groups. The game features encounters with individual rats, small groups, and a very
large group that identifies itself as "Many-as-One".

- In the video game Mass Effect, a galactic race known as the Quarians created a race of humanoid sentient machines known as the Geth. Geth are said to possess limited artificial intelligence and problem solving skills when alone, but automatically network with each other when in groups. This means that the machine's ability to solve problems increases in correlation with the size of the group.
- The television series Stargate SG-1 has entities known as replicators. Individually they only existed for their own survival, consuming and avoiding danger. However they also were able to link up all other replicators in the area. This made it possible like the Geth in Mass Effect to have vastly superior intelligence than would be expected from such a basic entity. This allowed them to defeat opponents that individually dwarfed them by a large extent in terms of intellect and size due to cluster computing.
- In the Commonwealth Saga by Peter F. Hamilton, the Dyson Aliens exhibit elements of swarm intelligence with their linked immotile brains and motile ancillary units.
- The novella Human Readable by Cory Doctorow is set in a future where ant-based routing is widely used for traffic and communications, and explores their potential drawbacks.
- The science fiction novel, The Swarm, by Frank Schätzing, deals with underwater single celled creatures who act in unison to destroy humanity.

Notable researchers

- Gerardo Beni
- Eric Bonabeau
- Marco Dorigo
- Luca Maria Gambardella
- Russell C. Eberhart
- James Kennedy
- Douglas A. Lawson
- Craig Reynolds
- Ken Rinaldo
- Dervis Karaboga
- Caro Lucas

References

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