Decentralized K-Means Clustering with MANET Swarms

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Abstract

Swarm intelligent systems are efficient, decentralized multi-agent problem-solving systems that offer several advantages over centrally controlled systems. A swarm intelligent system self-organizes into a structure that is robust, scalable, adaptable, and computationally efficient. Swarm intelligent systems, or swarms, utilize emergence, where simple local behaviors distributed across many agents lead to complex global phenomena, yielding a whole greater than the sum of parts. However, the relationship between the lower level agent behavior and the higher level emergent behavior is non-linear and not well understood, challenging the development of artificial swarms for engineering problems. Improved understanding of swarms can be realized by further instances of artifical swarms utilized for emergent problem solving.

A swarm intelligent solution is presented to a computationally challenging problem with quantifiable results in support of future models of emergence. The swarm intelligent Decentralized K-Means Clustering system is introduced within the context of rechargeable Mobile Ad hoc Networks (MANETs). Through engineered emergent behavior, cluster centroids relocate to reduce the cumulative distance between sensors and the nearest centroid, similar to K-means clustering, an NP-hard problem. An agent-based simulation is developed to evaluate the technique, which quantitatively demonstrates the effectiveness of the system.

1. INTRODUCTION

Picture a scenario where many small, stationary, wireless sensors are deployed in a large environment. Since limited battery life is a critical performance bottleneck for wireless sensor networks (WSNs), the system employs many wireless charging vehicles (WCVs) that traverse the environment and recharge sensors. WCVs first receive charge from a base station, then search the environment for a sensor, and recharge the sensor once in close proximity. After recharging the sensor, a WCV returns to a base station to recharge itself, before heading out once more in search of sensors. The system includes many base stations, which are mobile and capable or relocating. For the system to efficiently recharge the sensors, the mobile base stations should be placed as to minimize the cumulative distance traveled by WCVs.

However, for some reason, be it wireless interference, security, or privacy concerns, only local communication is possible, meaning information is only exchanged when a WCV returns to a base station. Non-local communication, such as a remote operator controlling a mobile vehicle, or long-range broadcasts of information, is not possible. A corollary of this constraint is that there is no sense of global positioning, such as coordinates, and the system is unaware of sensor locations. But then how can the WCVs navigate between the sensors and base stations? How can the base stations be intelligently placed without being told where to go?

The presented solution employs swarm intelligence, where the system self-organizes into a solution without any centralized control. Swarm intelligent systems are characterized by emergent problem solving capability, where simple behaviors aggregated across many agents give rise to a complex collective behavior. Emergence is often described as a whole greater than the sum of its parts, because the capabilities of the system arise from the synergistic interactions of the agents. Emergence is a concept easy to observe but not well understood, and recent work has investigated an emergent calculus [1], or quantitative models to support development of engineered swarms. By introducing a new swarm intelligent system capable of solving a challenging quantitative problem, further insight into an emergent calculus can be realized. For the aforementioned system, simple behaviors are assigned to the WCVs and base stations that result in emergent repositioning of base stations, which reduce the cumulative distance traveled by WCVs, in a swarm intelligent system deemed Decentralized K-means clustering.

2. SYSTEM OVERVIEW

A swarm intelligent system for clustering is introduced. Clustering is the unsupervised process of grouping together similar data objects. Typically, clustering is a centralized process because, among other reasons, all data is available to a central entity for computation. The Decentralized K-means clustering system is a multi-agent system without any centralized control. The system includes (i) stationary sensors, (ii) mobile base stations that act as the cluster centroids (the geometric center of clusters), and (iii) mobile WCVs that travel between the sensors and the base stations. The system self-organizes into clusters, where the mobile base stations relocate to reduces the total distance traveled by WCVs. The system is designated Decentralized K-means because of the similarity to K-means and related K-medians clustering, both

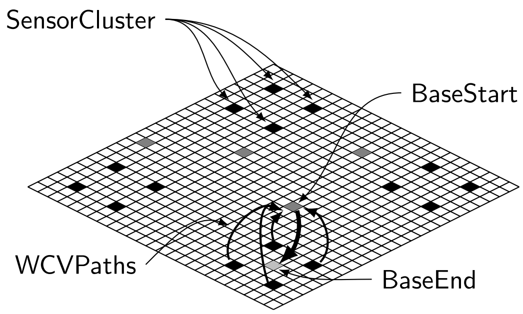

Figure 1: Illustration of Decentralized K-means clustering system, portraying how mobile base stations transition to locations minimizing the distance between base stations and sensor clusters (WCVs not pictures)

NP-hard problems [2].

The Decentralized K-means swarm is a modified ant system, namely, an adaptation of the ant foraging model introduced by Panait in [3]. In the Panait Ant Foraging (PAF) model, ants search a non-toroidal grid environment for food, moving to an adjacent cell with a certain probability. Ants deposit pheromones as they move through the environment, and ants are more likely to move to a cell with a higher pheromone concentration. Over time, while ants are deciding where to move based solely on local information, the collective ant colony uncovers the shortest path to food.

The PAF model is adapted for the Decentralized K-means system, where foods are now sensors, ants are WCVs, and nests are base stations. Though biologically inspired, the base stations are now mobile, unlike nests. In the Decentralized K-means system, WCVs begin by randomly searching for sensors in a non-toroidal grid world. While searching for sensors, WCVs deposit digital pheromones into the environment. After a sensor is located and recharged, the WCV begins following the pheromone trail back to the base station. Upon returning, the base station moves one cell in the direction of the returning WCV. The base station deposits pheromone before moving, so WCVs may continue to locate the base station by following the pheromone gradient. Over time, base stations relocate to positions that reduce the cumulative distance between the base station and sensors, illustrated in Figure 1.

3. AGENT-BASED SIMULATION

An agent-based simulation is developed to evaluate the Decentralized K-means system. The simulation includes 4 mobile base stations, 16 sensors, and 100 WCVs. The simulation is run for 10,000 time steps. All other parameters are held constant. Two scenarios are tested. In one scenario, the sensors are placed into 4 squares of 4, similar to the layout in Figure 1. Such a layout contains an easily identifiable global minimum, which was achieved in several simulated instances. Results are presented in Figure 1. Simulations are also run with sensors randomly distributed throughout the environment, with similar results. In all instances, the cumulative distance between sensors and nearest base stations is reduced.

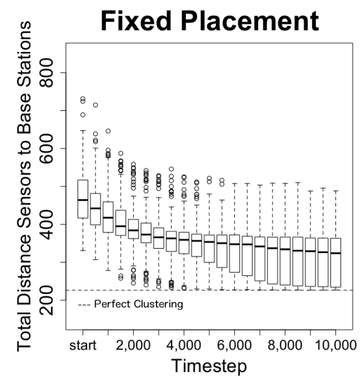

Figure 2: Box plots of 100 simulation runs portraying the decrease of cumulative distance between sensors and nearest base stations when sensors are distributed through the environment in square clusters, as seen in Figure 1

4. CONCLUSIONS AND FUTURE WORK

A swarm intelligent system is presented that self-organizes into clusters without any centralized control. An agent-based simulation is developed that quantitatively demonstrates the effectiveness of the technique. The system utilizes emergent behavior, a phenomenon commonly observed in nature but difficult to engineer. By providing a quantifiable instance of emergent problem solving, models of emergence, or an emergent calculus, may be further developed. Swarms are robust, scalable, adaptable, and computationally efficient. Swarms and emergent behavior offer an alluring alternative to centralized systems, which are reaching the limits of capabilities with the advent of Big Data.

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