An Urgency Dependent Quorum Sensing Algorithm for N-Site Selection in Autonomous Swarms

Extended Abstract

Grace Cai
Montgomery Blair High School
Silver Spring, MD
cai.grace.gc@gmail.com

Donald Sofge
Naval Research Laboratory
Washington, DC
donald.sofge@nrl.navy.mil

ABSTRACT

The ability for individuals and groups to trade off between decision time and decision accuracy when making decisions is commonly found in nature and essential for flexible decision-making responses. There has been little literature that models this ability in autonomous swarms, in which a large number of agents must come to a group consensus without a centralized controller. This paper successfully produces the first urgency-dependent model for discrete site selection by an autonomous swarm. It builds off of quorum sensing techniques found in natural swarms of ants and cockroaches as well as existing discrete site selection models for swarms to improve on previous work by adding the capability for agents to make a time-accuracy trade-off in decision making. The developed model will allow for future autonomous swarms to dynamically and effectively respond to a range of threats such as inclement weather and military attack.

KEYWORDS

Emergent behaviour; Analysis of agent-based simulations; Simulation of complex systems

ACM Reference Format:
Grace Cai and Donald Sofge. 2019. An Urgency Dependent Quorum Sensing Algorithm for N-Site Selection in Autonomous Swarms. In *Proc. of the 18th International Conference on Autonomous Agents and Multiagent Systems (AAMAS 2019), Montreal, Canada, May 13–17, 2019,* IFAAMAS, 3 pages.

1 OVERVIEW

This paper proposes an urgency-sensitive N-site selection design model for autonomous swarms. The model enables a swarm of autonomous agents to explore a search space for new sites, communicate with each other to determine the best option, and migrate to the new site after reaching a group consensus. We take inspiration from natural swarms as well as Reina *et al.*'s [12] and Cody and Adams' [3] N-site selection models. The model was tested in simulation on two, three, and four site selection in a 4.5 by 4.5 m arena and a time accuracy trade-off was successfully created with a maximum accuracy of 99.98% and a minimum decision time of 4.4 minutes. Split decisions also occurred with more urgent simulations due to a lack of communication at higher urgencies. The model framework presented in this paper could be applied to a range of discrete decision making problems that require a variation in exercising caution. The proposed model will conserve the resources required to build agents that need to complete dangerous tasks efficiently and effectively.

2 DYNAMIC QUORUM ALGORITHM

The swarm starts out in a site hereafter deemed the "nest" and must select the site with highest value among N sites, each with a location $L_i \in \mathbb{R}^2$, area $A_i \in \mathbb{R}$ [19], value v_i and distance d_i from their centroid to that of the nest. The situation has urgency u. The agents' decision time should decrease as urgency increases and their decision accuracy should increase as urgency decreases. Agents interact locally with a sensing radius of R_S and a communication radius of R_C.

In the proposed model, $u \in [0, 10],\ u \in \mathbb{R}$. Situation urgency is determined by the urgency function:

$$u = U(S_u) \tag{1}$$

S_u is a set of situation-specific parameters that affect the urgency of the situation. An example parameter is the presence of immediate risks such as mortar fire in military situations.

Each of six possible agent states is comprised of a preference category (Uncommitted (U), Favoring (F), or Quorum (Q)) and a location category (Active (A) or Nest (N)). Uncommitted agents do not have a site preference, Favoring agents prefer a site but may change their preferences, and Quorum agents have definitively decided on a site. Active agents stay outside of the nest, either exploring the arena or in a site, while Nest agents stay inside of the nest.

All agents begin in an uncommitted state in the nest. Uncommitted Nest (U^N) agents remain in the nest and do not participate in decision-making. Uncommitted Active (U^A) agents leave the nest and explore the arena for sites. The initial probability for an uncommitted agent to leave the nest and become Uncommitted Active is $x = \frac{u}{10}$. U^A agents transition to U^N every unit of time with probability P_N, and U^N agents transition to U^A with probability P_A, where P_N and P_A are governed by the following equations:

$$x = \frac{u}{10} \tag{2}$$

$$\rho(u) = \frac{x}{1-x} \tag{3}$$

$$P_N = \begin{cases} L & P_A < 1 \\ 0 & P_A = 1 \end{cases} \tag{4}$$

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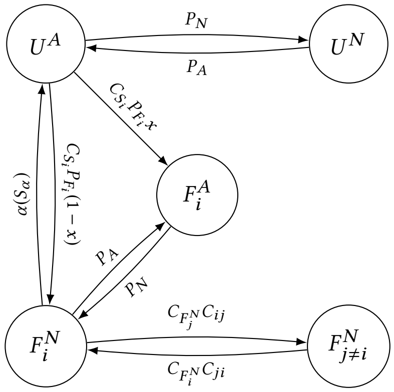

Figure 1: The Dynamic Quorum behavior model transitions for uncommitted and favoring states. Quorum states are omitted for clarity.

$$P_A = \begin{cases} \rho(u)L & \rho(u)L \leq 1 \\ 1 & \rho(u)L > 1 \\ 1 & x = 1 \end{cases} \tag{5}$$

As recommended with uncommitted states in Reina *et al.*, U^A agents transition to U^N every unit of time with probability $P_N = L$, where L is the inverse of the average site round trip [12]. In order to account for the urgency-dependent P_A transition, where at high urgency P_A may be equal to 1, P^N is also set to zero when this is the case. This enables U^A agents to have enough time to arrive at potential sites before returning to the nest. P_A is urgency dependent and set such that every 1 increase in urgency corresponds in a 10% increase of U^A agents. $\rho(u)$ determines the necessary factor to multiply L by such that the fraction of U^A agents out of all uncommitted agents is x.

U_A agents who detect a site within sensing range take time to examine the site and then decide to favor it with probability $C_{S_i}P_F$ where:

$$P_{F_i} = \frac{1}{2}(x + v_i \pm \varepsilon) \tag{6}$$

$$v_i = V(S_v) \tag{7}$$

P_F equally weights the situation urgency as well as the agent's perceived site value with some sensing error. Site value $v_i = [0, 1]$, $v_i \in \mathbb{R}$ is determined by V, the site value function, which takes in a set of situation-specific environment parameters S_v such as site area or potential dangers in a site. C_{S_i} is 1 if site i is within sensing range and 0 otherwise. After choosing to favor a site, agents then have an initial probability of being F^N with probability x and F^A otherwise. F^N agents communicate with each other in order to select the best site. The transitions between F^N and F^A are equal to those between U^N and U^A. Therefore with higher urgencies, a larger proportion of Favoring agents stay in their favored site. This behavior allows for favoring agents to build up a quorum in their site more quickly, allowing for quicker decisions with higher urgency values. This necessarily leaves less F^N agents in deliberation over site quality, which will result in a less accurate decision. At low urgencies, many agents participate in the deliberation process, resulting in a buildup of agents visiting the site of highest value. Favoring nest agents change each others' behavior through an inhibition process. When a F^N agent hears of a site valued higher than its own it visits the new site, explores it, and evaluates it. If the agent's evaluation confirms that the new site is of higher value, it switches to favoring the new site. As in Cody and Adams' and Reina *et al.*'s behavior model the probability for an agent to message another every second is L to promote sufficient population mixing so that excessive communication does not occur. The probability of the inhibition of an agent favoring site i by one favoring site j is $C_{F_j^N}C_{ij}$ where $C_{F_j^N}$ is L^*s_j, s_j is the number of agents favoring site j within sensing range, and C_{ij} is 1 when the agent's evaluation of site j returns a higher site value than its perceived value of site i.

Favoring agents can also abandon a site with probability $\alpha(S_\alpha)$ where α is an abandonment function that takes in a set of situation-specific parameters S_α that indicate a particular site is no longer favorable. An example parameter is the time since another agent was encountered in the site.

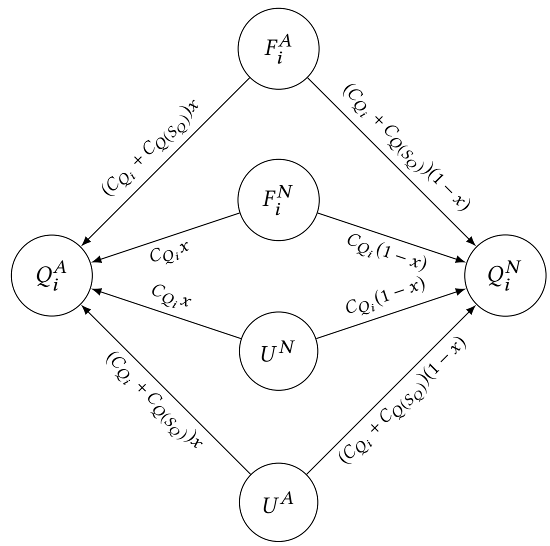

Figure 2: Transitions from Uncommitted and Favoring States to the Quorum decision states.

Active Uncommitted or Favoring agents detect a quorum while in a site with probability $(C_{Q_i} + C_{Q(S_Q)})$. C_{Q_i} is 1 when another quorum agent has been detected and 0 otherwise. $C_{Q(S_Q)}$ is 1 when the quorum function $Q_(S_Q)$ is satisfied but no quorum agents have been detected and 0 otherwise. Here S_Q is a set of situation parameters that should be relevant to a local measure of population density. Typical factors that S_Q would contain are the encounter rate of other agents within a certain amount of time or the number of neighbors within sensing range. Nest agents can also detect a quorum if a quorum agent is within sensing range.

After a quorum is detected all agents transition to Q^A with probability x and are Q^N otherwise. Once an agent transitions to a Quorum state it exhibits a random recruitment behavior to notify others of the quorum (for example, a Lévy flight) for a chosen amount of time t_Q before transitioning to the quorum site.

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