Self-Organized Collective Decision-Making in Swarms of Autonomous Robots

(Doctoral Consortium)

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ABSTRACT

In my Ph.D. thesis, I focus on the design and mathematical modeling of collective decision-making mechanisms for swarm of autonomous robots. In particular, most of the attention of my studies concerns collective decision-making problems that are characterized by a discrete and finite number of possible alternatives (e.g., the best-of-n decision problem discussed in Section 2). The aim of my studies is to develop mathematical models that enable designers to study collective decision-making mechanisms across different levels of abstraction: from mean field approximations that permit the study of asymptotic properties, to stochastic mathematical models that account for finite-size effects, and therefore, allow designer to predict the performance of actual systems.

Categories and Subject Descriptors

I.2.11 [**Distributed Artificial Intelligence**]: intelligent agents, multiagent systems

Keywords

collective decisions; swarm intelligence; self-organization

1. INTRODUCTION

Swarm robotics systems are distributed and self-organizing systems formed by a collective of autonomous agents (robots) inspired by the swarming behavior of some natural systems [4] (e.g., ant colonies, bee swarms). The problem-solving capabilities of such systems result from the local interactions of their components — the agents. In a swarm robotics system, agents are endowed with a set of simple control rules that are triggered by the agents' perception of the surrounding environment. Their main features comprise scalability with the size of the swarm, robustness to localized failures of some of the swarm individual components and adaptability to unknown environmental conditions.

The need for collective decisions is ubiquitous in swarm robotics systems. Common direction of motion, favored resource to exploit and division of labor are just few among several examples of collective decisions carried out by swarms of autonomous robots. Designers of swarm robotics systems need therefore to pay particular attention to the properties and performance of collective decision-making mechanisms (e.g., speed and accuracy trade-off, guarantees on the final decision, performance predictability). The analysis of collective decision-making mechanisms requires either to perform extensive agent-based simulations or to develop proper mathematical models that allow designers to answer their questions concerning the system.

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2. THE BEST-OF-N DECISION PROBLEM

At a very high level of abstraction, the best-of-n decision-making problem requires a collection of agents to establish an agreement on the most favorable choice among n available alternatives. Depending on the particular problem requirements, such an agreement may correspond either to a consensus or to a vast majority of the agents in the swarm favoring a particular alternative.

The best-of-n decision-making problem is a very general decision-making problem that can be reformulated for a number of different scenarios. Parker et al. [3] considered a nest-site selection task. In their scenario, robots needs to aggregate around the brightest spot available in the arena. Hence, the different alternatives correspond to different locations within the environment and their quality relates to the brightness of these locations. In Montes de Oca et al. [2] instead, a robot foraging scenario is reduced to the best-of-n decision-making problem. The different alternatives correspond to different paths between a nest and a certain resource, while their length defines the quality. Hence, shorter paths offer a better alternative to the robotic swarm. Finally, Campo et al. [1] recast an aggregation problem to the best-of-n decision-making problem. In their work, a swarm of robots is required to aggregate at the smallest available location that can host the entire swarm. As for Parker et al. [3], alternatives correspond to different locations within the environment but, in contrast, the quality of each alternative is now defined as the location's area.

During the development of my Ph.D. studies, I focused, in collaboration with other research colleagues, to the design and analysis of collective decision-making mechanisms for the best-of-n decision-making problem. The reminder of this section overviews the results achieved along this route.

2.1 The Majority Rule

In [5], we analyzed a system composed by a swarm of foraging robots that was originally proposed by Montes de Oca and collegues [2] under the name *majority rule with differential latency*. In this swarm robotics system, robots need to collectively decide between two alternative paths that link a pair of locations within the environment (source and destination areas). Each path leads to the same locations but may differ in the overall length, and hence, is characterized by a certain traveling time. The goal of the swarm is to build a consensus on the alternative associated to the shortest traveling time — the latency. Moreover, objects that need to be transported are too heavy to be carried by a single robot. A team of 3 robots is needed. Once formed, the team collectively decides which path to take considering the alternative favored by the majority. Eventually, this collective decision-making mechanism leads, with high probability, to consensus on the shortest available path.

In [5], we designed a time-homogeneous, absorbing Markov chain for collective decisions in a system with a finite number of robots whose dynamics are governed by the majority rule with differential latency model. Using our Markov chain model, we derived: (i) the exit probability, i.e, the probability that a system with a certain number of robots reaches consensus on the alternative associated to the shortest latency period; and (ii) the probability distribution of the number of applications of the majority rule necessary to reach consensus. With respect to previous studies on the same model, we showed that the system is characterized by a large variance of the number of decisions necessary before consensus [5]. Moreover, in contrast to previously developed continuous approximations, we explicitly modeled the state space of the system and the transition probabilities governing its dynamics. This approach allowed us to derive reliable predictions of a system regardless of its size.

2.2 The Weighted Voter Model

In [6], we introduced the *weighted voter model*, a self-organized collective decision-making mechanism for swarms of autonomous robots. The weighted voter model is designed to address the best-of-n decision-making problem over a nest-site selection task. That is, the swarm needs to find a consensus about which, among the alternative candidate sites, has the highest quality. The environment is partitioned into a nest and multiple candidate sites. The decision-making process takes place within the nest. An agent in the nest switch its current opinion about the best available site by taking the opinion of a randomly chosen neighbor. After every decision, agents leave the nest in order to explore their currently favored site and, in this way, they evaluate its quality. The time spent in the nest by each agent before changing opinion is proportional to the quality of its favored site. Following this mechanism, the weighted voter model leads the swarm to consensus on the opinion associated with the highest quality site.

In our recently published study [6], we analyzed the weighted voter model by means of both mean-field and finite-size mathematical models, respectively, using a set of ordinary differential equations (ODEs) and a master equation numerically solved by the Gillespie algorithm. Moreover, we developed agent-based simulations in order to validate the predictions of our mathematical models. The main advantages of the weighted voter model are its increasing decision accuracy with increasing system size, good scalability of the consensus time, and robustness to noisy assessments of site qualities. Using the ODE model we were able to guarantee convergence to the best decision for the thermodynamic limit and using Gillespie simulations of the master equation we were able to give guarantees for accuracy and consensus time for finite systems.

3. CONCLUSIONS

In my Ph.D. studies, I focus on the design and mathematical analysis of self-organized collective decision-making mechanisms. The primary attention of my studies concerns discrete decision-making problems with particular regard for the best-of-n decision-making problem. My aim is to analyze these kind of systems at different levels of abstraction by developing proper mathematical models, and thus, to provide designers with an analysis framework that enables them to answer common questions about the system under analysis.

As future directions of research, I plan to enhance the current modeling approaches for what concerns finite-size mathematical models. These models allows designers to quantitatively predict the performance of the system. However, their accuracy is limited by the underline assumptions. In general, assumptions concerning the spatial distribution of the agents within the environment tend to oversimplify the scenario of study, (e.g., well-mixed assumption, all-to-all interaction network), leading to a loss of accuracy in the prediction. My idea is to use concepts of network science in order to build a mathematical representation of the process spatial features in terms of networks and to use this representation in the development of mathematical models.

4. ACKNOWLEDGMENTS

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