Self-Organized Collective Decision-Making in a 100-Robot Swarm

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Abstract

We study a self-organized collective decision-making strategy to solve a site-selection problem using a swarm of simple robots. Robots can only move forward or turn in place; sense the intensity of the ambient light; and exchange 3-byte messages with peers in a limited range. The goal of the swarm is to collectively decide which of the sites available in the environment is the best candidate site. We define a distributed and iterative decision-making strategy: robots explore the available options, determine the options' qualities, decide autonomously which option to take, and communicate their decision to neighboring robots. We study the effectiveness and robustness of the proposed strategy using a swarm of 100 Kilobots and we focus on the impact of the neighborhood size over the dynamics of the system.

Introduction

In our research we study how large swarms of simple robots can take efficient and accurate decisions when functioning as a compact information processing entity by coordinating their actions using collective decision-making mechanisms. In this paper, we propose a self-organized collective decision-making strategy to solve a site-selection problem using a swarm or robots. Possible applications that may benefit from the scalability and robustness of swarm approaches include finding the target location in a human body where to deliver drugs or the most suitable location for construction in a hostile environment. The swarm is initially positioned in the *nest*, which is an area functioning as decision-making hub. The nest provides access to 2 equally distant *sites*, A and B. Robots in the swarm may sample the quality $\rho_i, i \in \{A, B\}$, of a site by exploring it and may use this information during the decision-making process. The goal of the swarm is to collectively agree on which site has the maximum quality. We implement our strategy in a swarm of 100 Kilobots (Rubenstein et al. 2014) and we show that it requires minimal robot capabilities.

We define a self-organized decision-making strategy that requires minimal perception and computational capabilities. Robots always have a preference for a particular site (henceforth, the robot *opinion*). The high-level control algorithm

of the individual robot is defined by a finite-state machine of 4 states (Fig. 1a). In the *dissemination* states (D_A, D_B) agents broadcast their opinion in a limited spatial range. Meanwhile, they perform random movements to stir their spatial distribution within the nest thus preventing the fragmentation of opinions. Prior to move to the exploration state, a robot determines its new opinion using the majority rule over a set of opinions which consists of the opinions of the robot's neighbors and its own current opinion. In the *exploration* states (E_A, E_B) robots travel from the nest to the site associated with their current opinion, explore the site, estimate its quality, return to the nest, and proceed to the respective dissemination state.

To promote the spread of the best opinion, robots spend a time in the dissemination which is proportional to the opinion's quality (either $\rho_A g$ or $\rho_B g$ where g is a design parameter). Consequently, robots favoring the best site have higher chances to influence the opinions of other peers. In this way robots directly control the positive feedback effect that drives the collective decision towards the best site.

Robotic Experiment

We implemented the above-described distributed algorithm in a swarm of Kilobots. The Kilobot is a low-cost, 3.3 cm robot with stick-slip motion (1 cm/s forward, $\pi/4$ rad/s turn in place), one ambient light sensor, and infrared communication capabilities (3-byte messages in a range up to 10-20 cm). We place $N = 100$ robots in a rectangular arena of 100×190 cm² (Fig. 1b). The arena is partitioned in three regions: site A at the right side; nest at the center; and site B at the left side. We consider a scenario where site A is twice as good compared to site B ($\rho_A = 1$ and $\rho_B = 0.5$). Robots can navigate between sites and nest using as a reference point a light source positioned at the right side of the arena. Due to the Kilobots' limited perception capabilities, we emulate the identification of sites and the estimation of their quality using infrared beacons positioned under the Perspex surface of the arena. Each beacon repeatedly broadcasts a message containing the type (A or B) and the quality (ρ_A or ρ_B) of a site. Robots perceive the beacons only at the site in the proximity of the border with the nest.

Depending on the current perceptions and on the control state, a robot alternates three low-level motion behaviors: random motion (*random walk*) and oriented motion to-
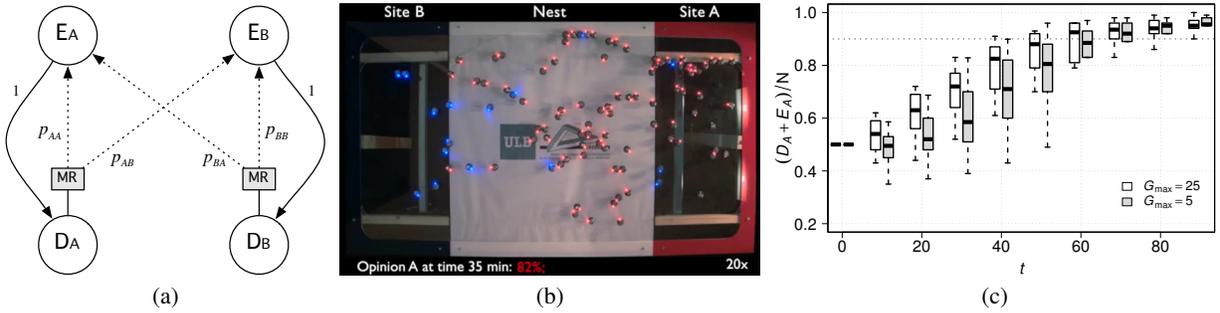
Figure 1: Illustrations of: a) the probabilistic finite-state machine of the individual agent; b) screen-shot of a robot experiment; and c) proportion of robots with opinion A over time during robot experiments.

wards or away from a light source (respectively, *phototaxis* and *anti-phototaxis*). In the dissemination state, robots perform a random walk within the nest and repeatedly broadcast their opinion. The duration of the dissemination state is determined by sampling an exponential distribution whose mean is given by either $\rho_A g$ or $\rho_B g$. If, while in the dissemination state, a robot perceives a message from a beacon, it recognizes that it is mistakenly leaving the nest; as a consequence, it enters either the phototaxis or anti-phototaxis behavior and returns to the nest. Before moving to the exploration state, a robot records the opinions of its neighbors, adds its own current opinion, and applies the majority rule to determine which site to explore (possibly switching opinion). In the exploration state, robots move towards the site associated to their current opinion (respectively, performing phototaxis if moving towards site A and anti-phototaxis if moving towards site B); they explore the area for an exponentially distributed period of time (period which, in a real scenario where robots are endowed with task-specific sensors, would corresponds to the actual estimation of the site's quality); and then return to the nest.

We study the effects of different neighborhood sizes $\mathcal{N}$ on the dynamics of the decision process. We perform two series of experiments (10 runs of 90 min for each series) where we vary the maximum number $\mathcal{N}_{\max}$ of opinion messages that a robot is allowed to receive before applying the majority rule. For convenience, we refer to the maximum size $\mathcal{G}_{\max} = \mathcal{N}_{\max} + 1$ of the group of opinions used in the majority rule which includes the robot current opinion ($\mathcal{G}_{\max} \in \{5, 25\}$). Fig. 1b depicts a screen-shot taken from one of the experiments. We show in Fig. 1c the dynamics of the proportion of opinion A during the decision process (($\mathsf{D}_A + \mathsf{E}_A)/N$). When $\mathcal{G}_{\max} = 25$, the swarm takes approximately 60 min to exceed a 90% majority for opinion A (white box-plots). When $\mathcal{G}_{\max} = 5$, the swarm exceeds the 90% majority in around 70 min (gray box-plots). We thus observe a positive correlation between the speed of the decision process and the average neighborhood size: the bigger the neighborhood, the faster the decision process. Additionally, Fig. 1c shows that even though the swarm establishes a large majority of $> 95\%$, the swarm does not reach a 100% consensus. This phenomenon is due to the fact that some robots suffer from poor locomotion performance

and would require recalibration during the experiment making them less likely to change opinion. Nonetheless, the proposed decision-making strategy proves to be robust to individual robot failures by enabling the swarm to establish a large majority for the best option.

Conclusions

We proposed a self-organized collective decision-making strategy that can be implemented in a swarm of 100 robots with minimal actuation, perception, and computational capabilities. Robot experiments show both the robustness of the decision strategy and the effects of spatial density on the velocity of the decision process. However, the time-cost of performing robot experiments limits the available data and therefore our analysis. In our accompanying article (Valentini, Hamann, and Dorigo 2014a), we defined a mean-field approximation model of the system dynamics to further investigate the effects of spatial density. Using this model, we show that consensus states are the only asymptotically stable solutions and that the speed of the decision-making process increases with the neighborhood size while its accuracy decreases. Finally, we analytically compared our strategy to a previously proposed strategy based on the voter model (Valentini, Hamann, and Dorigo 2014b) showing a considerable speed up of the decision process.

References

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