Engineering Applications of Artificial Intelligence 50 (2016) 302–319

Contents lists available at ScienceDirect

Engineering Applications of Artificial Intelligence

journal homepage: www.elsevier.com/locate/engappai

A Cooperative Switching Algorithm for Multi-Agent Foraging

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ARTICLE INFO

Article history:
Received 18 April 2015
Received in revised form
4 January 2016
Accepted 11 January 2016

Keywords:
Multi-agent system
Coordination
Stigmergy
Stigmergic Multi-Ant Search Area (S-MASA) algorithm
Multi-agent Search
Multi-Agent Foraging

ABSTRACT

The foraging task is one of the canonical testbeds for cooperative robotics, in which a collection of robots have to find and transport one or more objects to specific storagepoints. Efficiency in foraging can be improved with coordinated team of robots. Swarm robotics investigates the bio-inspired behaviors of simple species, that provide complex behaviors at the group level. We present a multiagent foraging algorithm named Cooperative Switching Algorithm for Foraging (C-SAF) inspired from the classical ant system. It provides a quick search, optimal homing paths and quick exploitation of food. A qualitative comparison between some foraging related works and the proposed algorithm is given here, as well as a quantitative comparison which shows that our algorithm outperforms the reference c-marking algorithm across a range of different scenarios.

1. Introduction

Multi-Agent Systems are a suitable approach to develop many multi-robot distributed applications such as: mine detecting (Acar et al., 2003; Gage, 1995), search in damaged buildings (Kantor et al., 2006; Jennings et al., 1997), fire fighting (Marjovi et al., 2009), and exploration of spaces (Landis, 2003; Schilling and Jungius, 1996), where neither a map, nor a Global Positioning System (GPS) are available (Batalin and Sukhatme, 2002). The efficiency of the group of robots in this case can be dramatically improved through coordination. Coordination issues (Yan et al., 2013) of multi-robot systems are considering more robots and more complex tasks, sometimes including robots and humans together. Swarm robotics investigates multi-robot coordination in a distributed way. It is interested in the implementation of systems which are composed of thousands of simple robots rather than one single complex robot (Vaughan, 2008). The challenge is to develop a group of robots with limited perception and computing capabilities to resolve complex tasks in a collective and distributed manner. This would allow for reduction of costs with respect to heavyweight approaches based on powerful and expensive cognitive robots/agents. In particular, stigmergic-based coordination mechanisms have been used in many robotics problems (aggregation formation and flocking WeiXing et al., 2006, patrolling Pasqualetti et al., 2010, localization and mapping Stipes et al., 2006, exploration and fire searching Marjovi et al., 2009), where agents adopt an indirect communication by depositing pheromone in their environment. This mechanism takes its inspiration from social insects (ants, bees, termites) which provide collectively intelligent systems (Momen, 2013) that, in spite of the simplicity of their individuals, present a highly structured social organization. As a result of this organization, ant colonies can accomplish complex tasks that in some cases far exceed the individual capacities of a single ant (Dorigo et al., 2000).

Foraging is a complex task that involves the coordination of multiple subtasks each constituting a difficult task (searching, harvesting, homing and unloading). It lends itself to multi-robot systems, even if the task can be achieved by one single robot, it is profitable to use multiple robots with careful design of cooperation and coordination strategies (Winfield, 2009). The sophisticated foraging behavior observed in social insects, provides inspirations to produce simple individuals (like ants) that use simple coordination rules and provide more complex (emergent) behaviors as a whole.

We investigate in this paper the Multi-Agent Foraging problem. Many approaches to such problem have been proposed in the literature so far (Momen, 2013; Hoff et al., 2010; Meng et al., 2012; Hoff

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http://dx.doi.org/10.1016/j.engappai.2016.01.025

et al., 2013; Lee and Ahn, 2011; Pitonakova et al., 2014). Here, we propose therefore the Cooperative Switching Algorithm for Foraging (C-SAF), an extended version of the Multi-Agent Foraging algorithms in Zedadra et al. (2015a) and Zedadra et al. (2015b). In this paper, we apply it to large-scale foraging systems with hundreds and thousands of agents, where we consider a wider range of system sizes than the ones in literature works (Hoff et al., 2013; Simonin et al., 2014; Shell et al., 2006) and in our previous work (Zedadra et al., 2015a). We analyze and qualitatively compare our proposed approach to relevant related works through an extension of a reference comparison framework (Winfield, 2009). An in-depth performance evaluation based on simulation is given that allows us to quantitatively compare our approach with cooperative and non cooperative foraging approaches. Results show that C-SAF algorithm takes on average less time to finish the foraging, returns larger food amounts and provides optimal food-to-nest paths without the need to revisit a cell several times. Moreover, it shows to be scalable and presents considerable parallelism with growing agent number. Finally, it outperforms the other approaches in terms of efficiency and scalability.

The remainder of the paper is organized as follows: Section 2 presents the background concepts and definitions, and the related work on foraging tasks. Section 3 describes the C-SAF algorithm. A qualitative comparison between C-SAF and the Non-Cooperative Switching Algorithm for Foraging (NC-SAF), c-marking and Non-Cooperative c-marking (NC-c-marking) algorithms, is presented in Section 4. Section 5 details the different scenarios, obtained results and quantitative comparison between the four analyzed algorithms. In Section 6, we provide a discussion on how to go towards a real robotic implementation of our approach. Finally, we draw conclusions in Section 7 and delineate some future works.

2. Background and related work

2.1. Basic concepts

Here we define and clarify some key terms and concepts that will be used throughout this paper:

- *Agent-Based Modeling* (*ABM*) is a class of computational models for simulating the actions and interactions of autonomous agents (both individual or collective entities such as organizations or groups) with a view to assessing their effects on the system as a whole and analyzing possible emergent behaviors.
- *Swarm Intelligence* is the study of natural and artificial systems of multiple agents that adopt a distributed autonomous control. Instead, global intelligent behaviors emerge from a cooperating collection of simple individual behaviors (Bonabeau et al., 1999).
- *Stigmergy* is a particular form of indirect communication mediated by modifications of the environment used by social insects to coordinate their actions (Grassé, 1959).
- *Artificial Potential Field* (*APF*) is a wavefront of integer values written by agents in the environment, to mark the short distance between any cell and the nest (Simonin et al., 2014).
- *Search* is defined as the act of looking into or over carefully and thoroughly in an effort to find or discover something (Méndez and Bartumeus, 2014).
- *Foraging* is the act of searching for and collecting food at one or more storage points. It is a complex task that involves the coordination of multiple other tasks, such as searching, homing, and grabbing (Winfield, 2009).

2.2. Multi-Agent Foraging problem definition on 2D grids

In the following, we present a formal definition of the Multi-Agent Foraging problem on two dimensional grids with one nest. The environment E is represented as 2D grid of cells of size $N \times N$. $E = E_{Free} \cup E_{Obstacles}$, where E_{Free} denotes the subset of E containing all obstacle-free cells and $E_{Obstacles}$ denotes the subset of E containing obstacles. $E_{Free} = E_{Reachable} \cup E_{Unreachable}$, where $E_{Reachable}$ denotes the subset of E_{Free} containing reachable cells (i.e. all cells that are reachable by agents) and $E_{Unreachable}$ denotes the subset of E_{Free} containing unreachable cells (i.e. cells enclosed in obstacles). $E_{Obstacles}$ is a subset of E defined as a set of obstacle cells where $Obs_i \subseteq E_{Obstacles}$. Each cell $c = (x, y) \in E$ has a maximum of four neighbors $(x-1, y), (x+1, y), (x, y-1), (x, y+1)$. Let c_0 be the origin (or nest) and the starting cell for all the agents positioned at the center of the environment (coordinates (0,0)). Let $E_{Visited}$ be the set of cells already visited where $E_{Visited} \subseteq E_{Reachable}$ and $E_{NotVisited}$ the set of cells not yet visited containing at the starting time all the cells of $E_{Reachable}$ except c_0 where $E_{NotVisited} \subset E_{Reachable}$ and $E_{Reachable} = E_{NotVisited} \cup E_{Visited}$. A is a set of identical agents $a_0 \ldots a_n$, where n is the total number of agents. Each a_i has initial heading (0°=up, 90°=right, 180°=down or 270°=left) and can perceive the four neighbors in up, right, down, and left directions. N food locations (referred to as food density), each with M food items (referred to as concentration) are spread on a set of cells included in the list C_{goal} (list of cells containing a food). Agents do not know the coordinates of the cells in C_{goal}. The goal is therefore to forage all food in C_{goal} by minimizing the $T_{foraging}$ time, i.e. the overall time needed to complete the foraging task. To guarantee completeness of search and reachability of food, we assume that obstacles do not partition E and do not enclose any agent, nest or food cell. Moreover, the problem definition can be easily generalized from one to many nests.

The components of our Multi-Agent Foraging system (*Environment, Agent, Pheromone*) are modeled as follows:

- *Environment Model*: The environment is organized as a N × N grid with several food locations, one or multiple sinks (or nests), obstacles and pheromone markings. The grid is divided into equal squares in a cartesian coordinate system. Grid maps are thought to an efficient metric for navigation in large-scale (Thrun and Bücken, 1996). Obstacles with rectangular or square shapes take place on some fixed cells, the nest is at the center (in a multi-sinks space, sinks take specific positions). N food with M items take fixed positions on the grid. In the offline version of searching, an agent has already the map of the world and plans its path before starting the search. Whereas, in the online version the agent plans the path directly when searching. The online version of the grid-based exploration has received considerable attention due to its applicability in practice since grids represent a natural discretization of planar environments (Thrun and Bücken, 1996). It is often used for solving tasks like path planning, localization, search, coverage and surveillance (Balch, 1996; Yean and Chetty, 2012; Lau et al., 2013; Panov and Koceska, 2014; Gabriely and Rimon, 2002; Choi et al., 2009). Apart from 2D-grids, that are the most used environments in the Multi-Agent Foraging problem, other approaches do exist. For instance, topological approaches such as those described in Mataric (1994); Gutjahr (2000) and Dorigo et al. (2006), represent robot environments by graphs. Nodes in such graphs correspond to distinct situations, places, or landmarks. They are connected by arcs if there exists a direct path between them.
- *Agent Model*: Agents are modelled as simple, reactive ant-like agents that can move in the four directions up, down, right and left,