Robotics and Autonomous Systems 58 (2010) 1282–1291

Contents lists available at ScienceDirect

Robotics and Autonomous Systems

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

Open-ended evolution as a means to self-organize heterogeneous multi-robot systems in real time

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ARTICLE INFO

Article history:
Available online 20 September 2010

Keywords:
Multi-robot systems
Open-ended evolution
Self-organization
Adaptation
Heterogeneous teams
Collective cleaning task

ABSTRACT

This work deals with the application of multi-robot systems to real tasks and, in particular, their coordination through interaction based control systems. Within this field, the practical solutions that have been implemented in real robots mainly use strongly coordinated architectures and assignment strategies because of reliability and fault tolerance issues when addressing problems in reality. Emergent approaches have also been proposed with limited success, basically due to the unpredictability of the behaviors obtained. Here, an emergent approach, called r-ASiCo, is presented containing a procedure to produce predictable solutions and thus avoiding the typical problems associated with these techniques. The r-ASico algorithm is the real time version of the Asynchronous Situated Co-evolution algorithm (ASiCo), which exploits natural open-ended evolution to generate emergent complex collective behaviors and deals with systems made up of a huge number of elements and nonlinear interactions. The goal of r-ASiCo is to design the global behavior desired for the robot team as a collective entity and allow the emergence of behaviors through the interaction of the team members using social rules they learn to implement. To this end, r-ASiCo manages a series of features that are inherent to natural evolution based methods such as energy exchange and mating selection procedures, together with a technique to guide the evolution towards a design objective, the principled evaluation function selection procedure. Hence, this paper presents the components and operation of r-ASiCo and illustrates its application through a collective cleaning task example. It was implemented using 8 e-puck robots in two different real scenarios and its results complemented with those of a 30 e-puck case. The results show the capabilities of r-ASiCo to create a self-organized and adaptive multi-robot system configuration that is tolerant to environmental changes and to failures within the robot team.

1. Introduction

The classical features associated with distributed systems, such as redundancy, fault tolerance, task distribution or unit simplicity are very relevant to real time applications, like those in industry. Currently, multi-robot systems (MRS) are one of the most prolific research fields in autonomous distributed systems due to their suitability for performing real world tasks such as cooperative cleaning [1], surveillance [2] or assembly [3]. However, even though advances in the control systems for these types of structures have greatly improved their level of autonomy, there is still a long way to go in order to make them really useful in real tasks.

The study of collective robotic systems and how the interaction of the units that make them up can be harnessed to perform useful tasks has taken inspiration, basically, from solutions that can be sought in nature and in the interaction of natural social systems, whether through simple trading strategies [4] or through more complex economic and social models [5]. In particular, the authors within the MRS real world application field have focused their attention on two elements that mainly determine the practical response of the system: the coordination architecture and the task assignment strategy. Regarding the former, several examples of coordination architectures may be found in the literature that range from strongly centralized and strongly coordinated systems to distributed ones with no explicit coordination, all of them providing successful application results in controlled domains [6]. However, when considering real world applications, system robustness and fault tolerance become mandatory, and these issues have been typically addressed through stronger coordination strategies that contemplate intentional communications as opposed to emergent approaches [7]. The main reason behind this decision is related to the control the designer has when using strongly coordinated strategies [8] as compared to the uncertainty of emergent coordination architectures that can make the MRS uncontrollable. In [9] the authors provide an extensive review of coordination strategies

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doi:10.1016/j.robot.2010.08.004

for MRS, showing how strongly coordinated systems are successfully applied to problems like multi-target observation (surveillance), exploration or object transportation.

On the other hand, it has been clearly demonstrated in the autonomous robotics field that these kinds of strongly coordinated strategies are very limited in terms of generalization and future improvements, requiring a lot of effort during their design and implementation in order to consider all the possible situations the MRS must confront during its operation. As a consequence, the coordination architectures obtained cannot really be classified as autonomous systems, where concepts like self-organization and adaptation are mandatory to deal with dynamic environments. Thus, a clear premise of the work presented here is that an autonomous MRS for real time tasks must be flexible in terms of coordination so as to be able to exploit the distribution and collaboration capabilities of a system made up of several components.

The second element that needs careful consideration in a practical multi-robot problem is the task assignment strategy. In this field, it must be assumed that the real task to be accomplished presents a high level of complexity and, in general, must be somehow divided to be fulfilled, either through its segregation into individual subtasks that can be distributed or through an interaction based approach where the interaction of a set of collaborators' behaviors leads to the overall task being performed. For the sake of generality, it is necessary to assume that the robots that make up the team may be heterogeneous, both in terms of hardware and of control. When heterogeneous hardware or control strategies are needed in order to achieve the tasks, it does not make too much sense (either economically or in terms of complexity) to consider the availability of a "super-robot" that is able to carry out all the different subtasks involved. Several authors have designed different approaches [10–12] to deal with their particular problems. Some of the most successful solutions for real time operation are auction based strategies [13,14]. They follow the same procedure as in real auctions, with a robot acting as an auctioneer to assign tasks and other robots bidding or not according to their objectives and capabilities. These strategies are independent of the heterogeneity or homogeneity of the MRS [15] and can be easily expanded. That is, an increase in the number of robots in the system does not imply a more complex allocation strategy. Their main drawback, however, arises in situations that require an adaptive response, because they lack some self-organizing properties as a consequence of the existence of fixed roles in the assignment strategy and of fixed steps in the execution of the auctions. In particular, an auction period must be established in which the robots are bidding, an auctioneer role is required, it is necessary to have a winner, etc. Thus, again, in the case of the assignment strategies, the main trends followed in the literature are usually too closed and present poor generalization perspectives. For these reasons, a second basic premise was established for this work in terms of seeking a simpler and more flexible self-organized task assignment strategy that emerges as a practical requirement of the task, and not as a prefixed decision of the designer.

Summarizing, coordination architectures and task assignment strategies for the real application of MRS must be revised to make them more flexible, reliable and general, so that they can provide real autonomy. To this end, this paper proposes the application of a natural open-ended evolution based methodology combined with a technique to guide evolution towards a design objective. This approach has been formalized as a new evolutionary algorithm called the Asynchronous Situated Co-evolution Algorithm (ASiCo), which has been tested in simulated engineering problems like surveillance [16] or freight shipping route optimization [17] obtaining self-organized and decentralized heterogeneous systems that collectively solve the task. The main objective of this work is to go one step further and present the real time version of ASiCo, called r-ASiCo, to take advantage of the adaptive capabilities of the algorithm in real applications of MRS.

The rest of the paper is structured as follows: the next section presents the background concepts of the ASiCo algorithm and reviews similar approaches that use open-ended evolution as a means to address real problems. Section 3 will focus on the formal presentation of the r-ASiCo algorithm, its basic elements, and its operation. A practical case of the application of r-ASiCo is presented in Section 4. The problem considered is a cleaning task that is carried out using a fleet of 8 e-puck robots. This task is initially formulated as a simple area cleaning task and it is then made more complex in terms of different types of cleaning and different constraints in order to test the self-adaptation and self-reconfiguration as well as the fault tolerance characteristics of the algorithm. Finally, Section 5 is devoted to a discussion on the perspectives of r-ASiCo and its implications.

2. ASiCo and similar algorithms

The Asynchronous Situated Co-evolution Algorithm (ASiCo) [16] is based on nature and on biologically inspired computational techniques [18,19]. In particular, it draws inspiration from the procedure followed to computationally simulate life-like dynamics and behaviors, as well as their evolution through the definition of local and low level interactions, as used in evolutionary Artificial Life (ALife) simulations [20]. Hence, it is based on the application of a representation of natural open-ended evolution, like in evolutionary Alife, because of its potential to generate emergent complex collective behaviors and to deal with systems made up of a huge number of elements and nonlinear interactions. As commented before, the main risk of these types of emergent approaches in real tasks is that of becoming unpredictable, which may not be acceptable when a fault-tolerant and reliable design is required. To solve this problem, the emergent behaviors in ASiCo are limited by the design objective of the evolution process. That is, the exploitation of a series of features that are inherent to natural evolution based methods and that may allow a degree of control over the open-ended process is sought here. In other words, instead of designing a set of very simple rules and analyzing the emergent system, as is usually the case in Artificial Life simulations, a more complex interaction pattern with a fixed objective is established through a manipulation of the evolutionary and survival rules to achieve the objective in a collective manner. Consequently, a technique to guide evolution towards a design objective has been introduced. It is based on the *principled evaluation function selection procedure* developed by Agogino and Tumer [21], which establishes a formal procedure to obtain the individual utility function of the elements that make up the system from a global function that includes the objective sought. Its particular implementation within the r-ASiCo algorithm will be detailed later in the practical example.

The application of open-ended natural evolution to real problems may be found in the literature of different engineering fields, mainly in the area of function optimization. In this line, [22–25] proposed several search algorithms, called emergent colonization algorithms, for the optimization of non-convex functions and for the optimization of time-dependent problems inspired on the dynamics obtained in ALife simulations. From such algorithms, Yang developed a parallel optimization procedure for engineering design applications. This procedure was successfully applied to the design of bearings [26]. Later, Ahn et al. [27] used a hybridization of a natural evolution based method and tabu search in the design of engine mounts. A more sophisticated approach was developed by Annunziato et al. [28–30], who applied a natural evolution simulation based procedure to the optimization of complex energy networks. In this work, the individuals in the population have some