Neurocomputing 148 (2015) 112–121

Contents lists available at ScienceDirect

Neurocomputing

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

Co-evolution framework of swarm self-assembly robots

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ARTICLE INFO

Article history:
Received 7 April 2012
Received in revised form
12 October 2012
Accepted 15 October 2012
Available online 31 July 2014

Keywords:
Co-evolution
Swarm robot
Genetic programming

ABSTRACT

In this paper, we present a co-evolution framework of configuration and control for swarm self-assembly robots, Sambots, in changing environments. The framework can generate different patterns composed of a set of Sambot robots to adapt to the uncertainties in complex environments. Sambot robots are able to autonomously aggregate and disaggregate into a multi-robot organism. To obtain the optimal pattern for the organism, the configuration and control of locomoting co-evolve by means of genetic programming. To finish self-adaptive tasks, we imply a unified locomotion control model based on Central Pattern Generators (CPGs). In addition, taking modular assembly modes into consideration, a mixed genotype is used, which encodes the configuration and control. Specialized genetic operators are designed to maintain the evolution in the simulation environment. By using an orderly method of evaluation, we can select some resulting patterns of better performance. Simulation experiments demonstrate that the proposed system is effective and robust in simultaneously constructing the adaptive structure and locomotion pattern. The algorithmic research and application analysis bring about deeper insight into swarm intelligence and evolutionary robotics.

1. Introduction

In nature, biological systems consisting of vast numbers of simple agents can attain functionally rich collective behavior and show impressive collective problem-solving capabilities [1], e.g., ant colonies, schools of fish, and multicellular organisms. The agents of nature allow cooperative and competitive working in large-scale societies. There exist two amazing collective phenomena [2]. First, the swarm agents can work collectively to profit from swarm capacity and intelligence, e.g., collective actuation, foraging, and exploration. Second, the swarm agents can aggregate into a multicellular organism that cannot be fulfilled by a single one or, in some cases, the swarms do not work collectively, e.g., in reaching target areas separated from the swarms by an object. Such biological phenomena have inspired the development of the robots, especially modular robots to improve adaptation.

We first present the swarm self-assembly robot, called Sambot, which has synthesized the strength of self-reconfigurable robots and self-assembly robots. Each Sambot is a completely autonomous mobile robot, similar to the individual robot in the swarm robotics. Multiple Sambots can form a robotic structure through self-assembly. A unified representation method is proposed to express the configuration. To derive the generic control model, we introduce the Central Pattern Generators (CPGs) by combining the previous unified representation method. Building upon the configuration and control model, a co-evolution framework is proposed to design the organism and the corresponding locomotion pattern that is composed of a swarm of robots. The algorithmic contributions of this work leads to a generic framework that co-evolve the configuration and control to allow the robot swarms forming the diverse patterns. In addition, we also present empirical results from implementing this algorithmic framework on a simulation experiment on co-evolution of the organism and locomotion control. Our proposed co-evolution framework is closely related to the evolutionary algorithm in modular robots [2–4]. Our work differs from other designs in the following two ways: (1) In the algorithmic aspect, we propose a generalized configuration and control model to give a unified genotype representation of all of the organisms even as the special operators are generating evolution. (2) In the aspect of application, the whole framework is established on existing swarm self-assembly systems. The systemic modules can autonomously aggregate and disaggregate to achieve a variety of organisms, which give the robot the potential to solve such issues of evolutionary organisms as configuration pattern, assembly, control, and encoding.

The rest of the paper is organized as follows: we begin with a related work review in Section 2. Section 3 introduces the Sambot simulation platform based on a realistic module, followed in

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http://dx.doi.org/10.1016/j.neucom.2012.10.047
0925-2312/

Section 4 by a representation of the symbiotic organism and a unity locomotion control model; Section 5 describes the co-evolutionary framework for achieving an adaptive combination of configuration and control to carry out an intended task; Section 6 demonstrates the simulation of the organism's adaptation; and finally, Section 7 concludes the paper.

2. Related work

The co-evolution of morphology and controllers has proved to be successful for performing particular tasks [5,6]. A genetic language using a directed graph of nodes and connections can define the nature of the creature. Virtual creatures are then expressed in a virtual environment to achieve fitness. These interesting virtual creatures interact with the external environment and then the best is selected. It is noted that in dynamic evolution a complex genotype-fitness relationship is implemented, and in this relationship genotype encoding plays a significant role. As for the evolved organism, encoding the phenotype consisting of unknown structures and adaptive controls is a complex process. Komosinsky et al. compared three encodings differing in several characteristics of the process of co-evolving morphology and the control of virtual stick creatures [7]. The fitness results demonstrated the properties of each encoding and the advantage of the evolved creature beyond that of the individual. Hornby and Pollack used the Lindenmayer system (L-system) as generative encoding to evolve neurally controlled robots from 2D to 3D, from simple parts to a complex organism [8]. Remarkable progress has been made in these studies on methodologies for the artificial co-evolution of robots; however, less attention has been paid to the component elements of the robot organism. As a population of cells, component elements can connect together and produce the offspring to generate a complex organism.

Through the application of bio-inspired or evolutionary methodologies, modular robotics has proven to be a perfect approach to fulfilling the potential of autonomous systems. Lipson proposed methods for generating both robotic structures and locomotion patterns using an evolutionary computation method [9]. Marbach performed a realistic simulation using a predefined type of module and started preliminary research on evolving both the configuration and control of homogenous robots [10]. Chocron encompassed the design of three types of basic modules and used an evolutionary algorithm to achieve some locomotion tasks [3]. Based on a morphogenetic modular robot, Meng et al. used a two-layer hierarchical morphogenetic approach to generate the goal pattern responding to the changing environment in simulation [4]. Due to its complexity, an evolution application in real robot hardware is not available at present, but the idea of the co-evolution of configuration and control can be introduced. To achieve the adaptive furniture, the reconfiguration approaches and adaptive control method were applied to modular robots, called Roombot, in unstructured environments [11]. As a modular unit, robot swarms can aggregate into an interesting organism. Some scenarios that have been envisioned are symbiotic robot swarms that can form an organism to serve a special requirement [2]. The above studies have led to the promising result that evolved organisms are possible in theory. Most studies on co-evolutionary robots present a theoretical design and simulation application with no regard for module designs such as module motion, the degree of freedom, and so on. Although some hardware scenarios have been demonstrated [12], it is difficult to generalize the prototypes to the co-evolution of complex organisms. These prototypes take little consideration of the whole system, including what locomotion pattern is required, what configuration structure and control system can be used to make the robot organism and how to autonomously construct the robot organism. None of the prototypes can realize the autonomous evolution from cells to organism without initial configuration settings or external directions.

Here, the idea of co-evolution and the law of the survival of the fittest are introduced in self-assembly robots to achieve the co-evolutionary development of the configuration and control system of the robot organism. Our co-evolution framework has been applied on the simulation platform and also will be available on realistic hardware platform.

3. Sambot robot and simulation platform

3.1. Sambot robot

Sambot is an autonomous mobile and self-assembly modular robot that can form a symbiotic or multicellular organism by modules moving autonomously and docking with each other [13–15]. The overall size of the module is $80 \times 80 \times 102$ mm. As an autonomous independent unit like a cell, each module is homogenous and possesses the following capabilities:

(1) *Sensor.* Each robot module is equipped with a number of infrared sensors to measure distance, as shown in Fig. 1 ⓐ; gyroscope to measure direction, etc.; and so on. Here, these infrared sensors can guide the robot to seek another robot module and finish the precise docking procedure.
(2) *Moving.* Each robot is capable of autonomous motion using the wheels below the robot body, as shown in Fig. 1 ⓑ. This

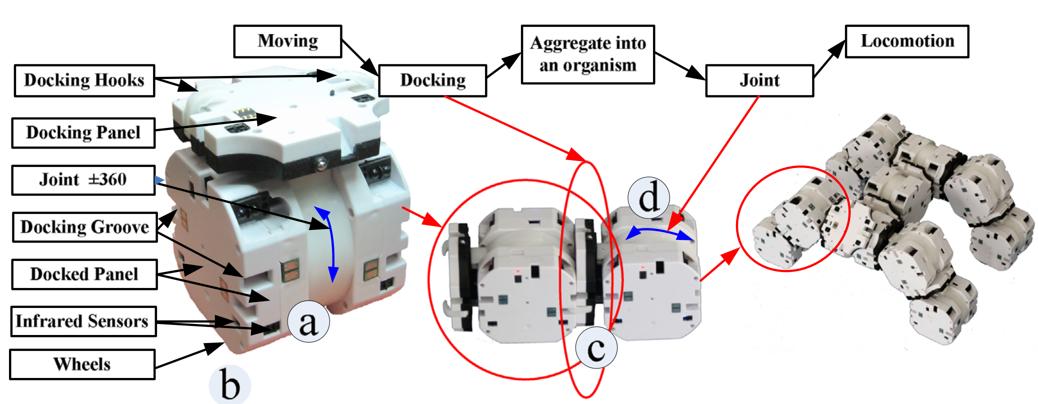

Fig. 1. Left: The Sambot robot can move as an autonomous unit. Middle: Through docking, a set of robots can aggregate into an organism. Right: By the articulated drive between the neighboring modules, the robot can locomote.