Robotics and Autonomous Systems 59 (2011) 1090–1101

Contents lists available at SciVerse ScienceDirect

Robotics and Autonomous Systems

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

Collective energy homeostasis in a large-scale microrobotic swarm

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ARTICLE INFO

Article history:
Received 21 September 2006
Received in revised form
28 July 2011
Accepted 4 August 2011
Available online 19 August 2011

Keywords:
Energy
Energy efficiency
Robotics
Swarm
Self-sufficiency

ABSTRACT

This paper introduces an approach that allows swarm robots to maintain their individual and collective energetic homeostasis. The on-board recharging electronics and intelligent docking stations enable the robots to perform autonomous recharging from low energy states. The procedure of collective decision-making increases collective efficiency by preventing bottlenecks at docking stations and the energetic death of low-energy robots. These hardware and behavioral mechanisms are implemented in a swarm of real microrobots, and several analogies to self-regulating biological strategies are found.

1. Introduction

Homeostasis is one of the distinctive properties of living organisms [1]. The evolutionary sensor–actuator development of living organisms and their behavioral and reproduction strategies depend on certain parameters of their internal regulatory mechanisms [2]. The most important of these is energy balance and, closely connected to this, foraging behavior and strategies [3].

Homeostasis in technical systems differs from biological organisms primarily in the non-autonomy of the energy balance [4]. Technical systems, such as mobile robots, depend on human participation in their energy supply. The energy problem is especially challenging in microrobotic systems [5]; state of the art solutions for autonomous recharging in robots are exemplified by on-board electronics, sensors and power stations (see for example [6] or [7]); alternative approaches are represented by, for example, microbial fuel cells [8] and energy harvesting [9]. Work has been published concerning models of robot foraging [10], bio-inspired energy harvesting strategies [11] and more generally on foraging and scalability; see for example [12].

When autonomous robots have energetic homeostasis, their behavior does not depend solely on behavioral goals defined by a designer [13]. Such robots monitor their energy state, save energy by choosing optimal behavior and autonomously seek recharging stations. In this, we perceive several analogies with biological organisms [14]. To some extent, robots can "feel" hungry, can look for a food source and can exercise certain degrees of behavioral freedom to avoid energetic death. In this way, these biological concepts are re-embodied in robotics [15]. This problem becomes especially hard when many robots perform cooperative energy foraging. Depending on the current energy level in the swarm, these robots can collectively choose different foraging strategies: to allow the robots with the lowest energy to recharge first, in case they do not survive; an altruistic strategy in which all robots recharge for a short time and thus maximize the common energetic level; or an egoistic strategy of maximum individual recharging and competition for resources. These are analogous with the behavioral strategies of animals in regions of distributed food resources [16].

In this paper, we demonstrate autonomous recharging in a microrobotic swarm [17] and investigate the swarm's collective energy homeostasis. This includes the development of relevant hardware and software components for individual robots. The technological constraints of the running and recharging times imposed by the docking and recharging processes define the behavioral strategies for all the robots. The docking station is equipped with a communication system compatible with the robots' [18] and allows the robots to sense the availability of energy. To regulate collective behavior, we implement a procedure for collective decision-making. Since the microrobots have limited computation and communication capabilities, their collective decision-making is based on randomly-coupled map lattices [19], which do not demand sophisticated computation and communication resources. The mechanism used either changes the priority and duration of individual recharging or adjusts individual duty cycles, allowing the robot swarm to adapt to the energetic conditions in the environment. This self-regulation mechanism

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doi:10.1016/j.robot.2011.08.001

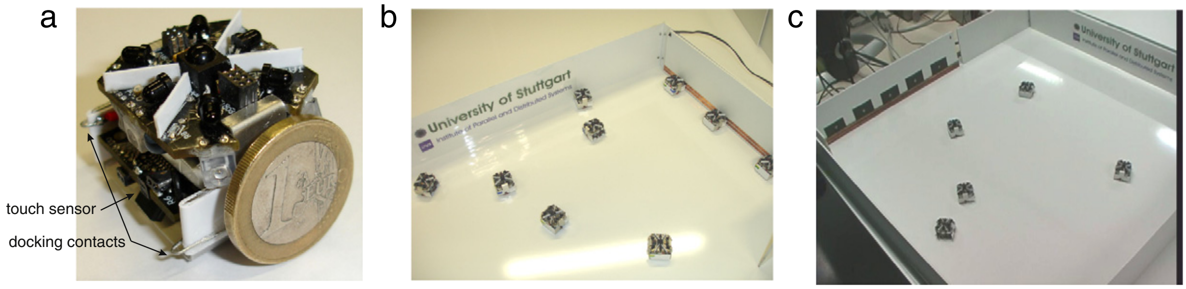

Fig. 1. (a) The "Jasmine" microrobot's recharging contacts. The touch sensor on the front of the robot is also shown. (b) The first docking station, at which each robot can become a communication point. (c) The second docking station, with integrated communication points.

is highly-scalable with regard to swarm density, and introduces the so-called "tech-inspired" approach, in contrast to previously published bio-inspired approaches, for example [11,20].

The paper is organized thus: in Section 2, we describe the hardware components of the robot and the technological constraints imposed on its behavior; Section 3 deals with energetic homeostasis and the software components; Section 4 treats the suggested collective strategy that allows the robots to cooperate in foraging; Section 5 demonstrates the implementation and the experiments performed; and finally, Section 6 offers conclusions from this work.

2. On-board recharging hardware

The "Jasmine" microrobot, shown in Fig. 1(a), measures $30 \times 30 \times 20$ mm^3 in size and has two small DC motors with an integrated planetary gearbox. The microrobot has two circuit boards, the motor board and the main board, which communicate via a 200 kHz I2C interface. The main board holds an ATmega 168 microcontroller, six (60° opening angle) IR channels (used for proximity sensing and communication) and one IR geometry-perception-channel (15° opening angle). The sensing area covers a 360° rose-like area with maximum and minimum ranges of 200 mm and 100 mm respectively [17]. The physical communication range can be decreased through a change of sub-modulation frequency. The main board also supports remote control, differential light sensing, energy management, ZigBee communication and is primarily used for the behavioral control of the robot and for upper extension boards. The motor board has an ATmega 88 microcontroller and is used for motor control, the odometrical system [21], energy control, touch (short-range reflective IR sensor), and color sensing; it also provides another four channels for further sensors/actuators.

To make the microrobots capable of autonomous recharging, four components are required: (a) internal energy sensors, monitoring the energy level of the Li–Po accumulator; (b) recharging circuitry for the Li–Po process; (c) reliable connection with the docking station with low electrical resistance; (d) communication with the docking station. The internal energy sensor is implemented as a resistive voltage divider with a coefficient of 0.55, connected directly to the Li–Po accumulator. The overall resistance is 726k (402k + 324k), and the continuous drain current is about 5 μA. The ADC conversion takes about 64 μs, so monitoring of the energy level can be achieved relatively quickly.

The microrobot uses a single-cell 4.2 V Lithium–Polymer accumulator with a capacity of 250 mAh. The robot consumes about 200 mA when moving and sensing, about 20 mA when sensing only (communicating) and about 10 mA when listening only. Thus, the running time of the robot is approximately 1.25 h. In its optimal working mode, the Li–Po accumulator discharges only 75%–80% of its capacity. The accumulator reaches critical level when the voltage drops to less than 3 V. At this point, the internal power regulator is not able to stabilize the voltage fluctuations and the microcontroller can spontaneously reboot. The recharging current is 1C (250 mA), and full recharging takes about 90 min Partial recharging is almost equal to discharging (that is, 15 min motion requires about 15 min recharging). To control the recharging process, we use the linear Li–Ion/Li–Po battery charger LTC4054-4.2 in a small ThinSOT package.

For autonomous recharging, we developed a simple and reliable solution for the docking station [22]: two 0.4 mm silver-plated wires glued to the front of the robot. The connectors are installed at different heights, see Fig. 1(b) or Fig. 1(c). The docking station comprises a wall to which are attached two strips of copper, 0.2 mm thick by 5 mm wide. Both copper strips are connected to the power supply, which can provide 5 V and 3 A current. The length of the docking station is chosen to allow the simultaneous recharging of 5–10 robots, see Fig. 1(b). Many such docking stations can be placed together, see Fig. 9. To connect to the docking station, a robot has to move to this wall (after receiving the docking signal), until it receives a positive signal from the touch sensor. Then, the robot turns slightly on its wheels, producing a small mechanical strain to maintain reliable mechanical contact. The resistance of such a contact is less than 0.1 Ω (measured statistically).

2.1. Communication with the docking station and docking approach

The development of the docking station and the docking approach has been addressed in several publications, such as [11,22–24,20]. After testing many solutions, we eventually used two setups that demonstrated the best reliability for docking. In the setup shown in Fig. 1(b), every docked robot can became a communication point to guide other robots to the station. The initial communication point is represented by a robot that remains at the left boundary of the docking station and does not move. When a robot approaches the station, it sends a request signal to the station and listens for an acknowledgment. If it receives an acknowledgment, it moves straight to the communication point and sends the request again. No acknowledgment means a free slot exists. The direction of the free slot is given by the receiving sensor, that is, if it is the first sensor, that means a docking slot exists in front, if the second sensor, the robot needs to rotate 30°, and so on. When necessary, a robot rotates and moves forwards until it receives a touch confirmation from the touch sensor. Through monitoring the voltage on the energy sensor, the robot is made aware of the start of recharging. After a robot is docked to the station, it sends the docking acknowledgment to any requesting robots through its rear transmitter.

The setup in Fig. 1(c) uses integrated communication points (the main boards from the robot) at each docking slot. The docking station continuously sends the availability signal and number of free docking positions. This signal can be received up to 10–15 cm away from the docking station. A robot receiving the docking signal for free slots approaches the docking station and sends