Available online at www.sciencedirect.com
ScienceDirect
Robotics and Autonomous Systems 54 (2006) 789–804
Robotics and Autonomous Systems
www.elsevier.com/locate/robot

Micromanipulation, communication and swarm intelligence issues in a swarm microrobotic platform

P. Valdastri[a,*], P. Corradi[a], A. Menciassi[a], T. Schmickl[b], K. Crailsheim[b], J. Seyfried[c], P. Dario[a]

[a] *Scuola Superiore Sant'Anna - CRIM Lab, V.le R. Piaggio 34 – 56025 Pontedera (PI), Italy*
[b] *Department for Zoology, Karl-Franzens-Universität Graz, Universitätsplatz 2, A-8010 Graz, Austria*
[c] *Universität Karlsruhe (TH), IPR, Building 40.28, Kaiserstraße 12 – 76128 Karlsruhe, Germany*

Received 18 April 2005; received in revised form 8 May 2006; accepted 15 May 2006
Available online 5 July 2006

Abstract

Rapid advancements of both microsystem technology and multi-agent systems have generated a new discipline, arising from the fusion of microrobotics technologies and of swarm intelligence theories. Microrobotics contributes with new capabilities in manipulating objects in the microscale and in developing miniaturized intelligent machines, while swarm intelligence supplies new algorithms allowing sets of simple robotic agents to solve complex tasks. A microrobotic swarm that is able to collectively achieve a cleaning task in an arena has been developed. This paper presents a novel platform for microrobotic swarms with the goal to apply swarm intelligence results to practical micromanipulation tasks and describes in details two main features of the platform: an optical communication strategy between the microrobotic agents, in order to share information and to coordinate swarm actions, and a micromanipulation technique – based on electrostatic phenomena – which can be performed by each microrobotic agent.

Keywords: Microrobotics; Swarm intelligence; Optical communication; Electrostatic grasping; Electrostatic releasing

1. Microrobotics and swarm robotics

A growing worldwide interest in microrobotic devices is today evident, including micromanipulation tools and microconveyers and/or microrobots as locomotive mechanisms. The general term "microrobots" can be better classified into three different subcategories:

- Miniature robots or minirobots: size on the order of a few cubic centimeters and fabricated by assembling conventional miniature components;
- MEMS-based microrobots (or microrobots): a sort of "modified chip" fabricated by silicon MEMS-based technologies having features in the micrometer range;
- Nanorobots: scale similar to the biological cell (on the order of a few hundred nanometers) and fabricated by molecular engineering.

Microrobotics has a particular relevance in the development of a relatively new scientific discipline named "Swarm Robotics". Swarm robotics can be defined as the study of how a large number of relatively simple agents can be constructed/programmed to collectively accomplish tasks that are beyond the capabilities of a single one. Differently from other studies on multi-agent systems, swarm robotics focuses on the concepts of self-organization and emergent behaviors, while considering the issues of scalability and robustness. This aspect involves the use of relatively simple robots with local sensing abilities, and the exploitation of scalable communication mechanisms and decentralized control strategies. It is in the perspective of miniaturization that swarm-based robotics becomes meaningful [7], therefore leading to the concept of "swarm microrobotics". "Microrobotic Swarms" consist of hundreds of mobile robots, a few cubic millimeters in size. The capabilities of the single unit are consequently limited and, therefore, microrobots need to operate in very large groups or swarms to affect the macroworld. Mass fabrication microtechnologies have the potential to produce a large number

* Corresponding author. Fax: +39 050883497.
E-mail address: pietro@sssup.it (P. Valdastri).

0921-8890/$ - see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.robot.2006.05.001

of units at low costs, while the swarm intelligence approach can compensate the limited capabilities of the single units – due to their size – with an emergent coordinated and collaborative swarm behavior. Currently, there are several ongoing projects that aim to develop and control large numbers of physically embodied agents. Self-organizing and cooperative behaviours have been investigated for navigation, for pattern formation [34,38,55], and for doing tasks too complex or impossible for a single robot to achieve [8], like cooperative pushing [27]. Decentralized control and reactive behaviour on local perception have been implemented for object clustering tasks [5,20,30] and object sorting [32].

A very promising branch of swarm robotics is self-assembly swarm-based robotics. This discipline studies systems in which quite small and capability-limited robotic modules can assembly and reconfigure autonomously in larger robotic structure capable of performing tasks that the single sub-module is not able to. The concept was first investigated in [39] and introduced in robotics in [19]. Main realizations are addressed in [13,22,35,37].

2. The I-SWARM project: Objectives and addressed issues

The I-SWARM project (Intelligent-Small World Autonomous Robots for Micromanipulation, http://www.i-swarm.org) combines expertise and knowledge in microrobotics, in distributed and adaptive systems as well as in self-organizing biological swarms. By exploiting advanced fabrication technologies, the project goal is to mass-produce many microrobots which can then be employed as a "real" swarm consisting of up to 1000 robotic agents. In swarm robotics, motivations and scenarios are always close to natural counterparts. This is due to the fact that swarms[1] exhibiting all desirable properties (e.g. stability, flexibility, robustness, scalability and simplicity of the agents [7,10,26]) have not yet been built artificially, and thinking in a "swarm-like" way seems to be relatively hard for an organism with a strong emphasis on the individual (like humans are). At the same time, it is relatively hard to re-create mechanisms like those nature uses to create self-organization effects (feedback, positive or negative, or fluctuations) in robotics. For example, chemicals, called *pheromones*,[2] are very often used in nature for swarm-level navigation tasks, exhibiting all the well known self-organization effects. Generation, deposition and detection of chemical substances still pose a great and almost unsolved challenge to a technical system.

Therefore, numerous ways to imitate the concepts that are used by biological swarms have been researched in the past (e.g. the "virtual pheromone": this can be simulated by a projected light gradient [25], or by robot-to-robot communication [38], or by magnetic footprints [3], or other principles).

[1] Please note that within the "swarm intelligence" community, the term "swarm" is frequently used for systems that biologists would rather call "colony" instead. We will stick to this habit throughout this article.

[2] Pheromones are chemical substances that are emitted by animals to the outside environment. Other animals that perceive these pheromones (even at low dose) react with specific behaviours, e.g. aggregation.

The ability of a single robot to communicate, directly or indirectly, with other members of the swarm, is mandatory in order to establish the cooperative interaction, which is necessary for generating emergent behaviors. This article presents a scenario of collective floor cleaning that has to be performed by a swarm of microrobots. We suggest feasible micromanipulation techniques to grasp obstacles, swarm-level communication by using light pulses and a bio-inspired communication strategy that uses vector information that is passed among the swarm members to navigate the robots in their environment. A suggested robot swarm that implements all these features was simulated and shaped by artificial evolution, showing interesting and surprising features and constraints.

3. Hardware features of the suggested microrobot swarm

3.1. Communication platform

The ability to sense and to communicate is of paramount importance for large multi-agent systems in which continuous interaction with the environment and neighbors is necessary, in order to explore, perform collective tasks and share information. This last aspect is a capital element both in natural and robotic swarms, where inter-robot communication (direct or indirect) is the base of emergent behaviours. In order to realize such communication capabilities in microrobotic swarms, an integrated, miniaturized, low power communication (and sensing) system is crucial.

The original approach for developing swarm communication strategies and the related hardware tends to biomimicry. Nature offers plenty of examples of colonies of insects and flocks of other animals, which clearly demonstrate swarm intelligence. In particular, the collective strategies demonstrated by some insects (e.g., ants, bees, wasps and termites) have been targeted as the most interesting examples to be imitated. These strategies include decentralised colony homeostasis [43], dynamic regulation of division of labour [6,9,50] and collective selection of feeding sites and nesting sites [44,45,47,49]. It depends not only on the small size, comparable with our microrobot concept, but also on the lower intelligence and complexity of the single unit, which is more likely to be emulated, both from the viewpoint of capabilities and of computational power.

Communication is strongly related to the microrobot size and power available onboard. The first implies that only highly miniaturized communication systems can be integrated, while the latter imposes strict limits on communication distance capability.

There are several examples of wireless techniques for inter-robot communication in multi-agent systems. Radio frequency (RF) and optical communication have been so far the most applied solutions. RF communication has been extensively used down to the range of one-centimeter large robots [11], in a frequency band ranging from 30 MHz to 3 GHz. One of the main problems related to the integration of RF systems on very small robots (millimeter range) is related to the required