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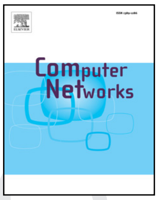

Fast and robust self-organization for micro-electro-mechanical robotic systems

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ABSTRACT

Microrobots are low-power and low-capacity memory devices that can sense and act. They perform various missions and tasks in a wide range of applications including odor localization, firefighting, medical service, surveillance and security, search and rescue. To achieve these tasks nodes should reconfigure their physical topology to another target organization. The self-organization is one of the most challenging tasks in MEMS applications. In this paper, we propose a distributed and efficient parallel self-organization protocol for chains of MEMS nodes. This protocol is memory-efficient because it does not use the predefined positions of the target shape, which reduces the memory usage to a constant complexity. Our algorithm is implemented in a real environment simulator called DPRSim, the Dynamic Physical Rendering Simulator.

1. Introduction

Micro electro mechanical systems (MEMS) microrobots are miniaturized and low-power distributed and autonomous devices that can sense and act. It is expected that these small devices, referred to as MEMS nodes, will be massed produced, making their individual cost almost negligible. MEMS microrobots are potentially very cheap, particularly through their use in many areas in our daily life, including odor localization, firefighting, medical service, surveillance and security, and search and rescue. Their applications require a massive deployment of nodes, thousands or even millions [8,33] which will give birth to the concept of Distributed Intelligent MEMS (DiMEMS) [4].

The size of MEMS nodes can vary from well below one micron on the lower end of the dimensional spectrum, all the way to several millimeters. A DiMEMS device is composed of typically thousands or even millions of MEMS nodes. Some DiMEMS devices are composed of mobile MEMS nodes [1,3], some others are partially mobile [36] whereas other are not mobile at all [4].

One of the major challenges in developing a microrobot is to achieve a precise movement to reach the destination position while using a very limited power supply. Many different solutions have been studied, for example, within the *Claytronics* project [1,2,9,13,22] each microrobot helps its neighbor to move to the desired position, which introduce the idea of a collaborative way of moving. However, even if the power requested for moving has been lowered, the moving still costs a lot regarding the communication and computation requirements. Optimizing the number of movements of microrobots is therefore crucial in order to save energy. Within the *Claytronics* project, each node can see only the state if its physical neighbor, this can be explained as a shared memory between physical neighbors. Therefore, the aim is to develop algorithms where each node uses only local information.

In the literature, the self-reconfiguration can be seen from two different points of view. First, it can be defined as a protocol, centralized or distributed, which transforms a set of nodes to reach the optimal logical topology from a physical

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topology [11]. On the other hand, the self-reconfiguration is built from modules which are autonomously able to change the way they are connected, thus changing the overall shape of the network [9,26,29]. This process is difficult to control, because it involves the distributed coordination of a large numbers of identical modules connected in time-varying ways. The range of exchanged information and the amount of displacement determine the communication and energy complexity of the distributed algorithm. As said before the MEMS nodes have a very small size. Therefore, due to their small size, to cover a target shape it is required to divide this target shape to very small units (according to the size of the node) which will give millions of positions. If we use the solutions in literature works each node should have a memory capacity of at least millions of positions if the size of the target shape is composed of millions of positions, hence the importance of providing self-reconfiguration solutions without predefined positions of the target shape.

An open issue is whether distributed self-reconfiguration would result in an optimal configuration with a moderate complexity in message, execution time, number of movements and memory usage.

In this paper, we propose a new distributed approach for parallelized self-reconfiguration of MEMS microrobots, where the target form is built in parallel incrementally, and each node can predict its number of movements to make the algorithm robust. Because the node can make sure that it has correctly followed the algorithm. We introduce a state model where each node can see the state of its physical neighbors to achieve the self-reconfiguration for distributed MEMS microrobots, using the states the nodes collaborate and help each other. Contrary to existing works, in our algorithm each node has no information on the correct positions (predefined positions) of the target shape. The self-reconfiguration with shared map (predefined positions of the target shape) does not scale. Because with the map each node should store all predefined positions (may be millions) of the target shape, this is not always possible as MEMS nodes have a low- capacity memory.

We propose an efficient, distributed, asynchronous and parallelized algorithm for nodes self-reconfiguration where each node can communicate only with its physical neighbors. We study the case of a self-reconfiguration from a chain of microrobots to a square. The performance of the self-organization algorithm is evaluated according to the number of movements, the amount of memory used and the time taken. In this paper the MEMS network is organized initially as a chain. By choosing a straight chain as the initial shape, we aim to study the performance of our approach in extreme case. Indeed, the chain form represents the worst physical topology for many distributed algorithms in terms of fault tolerance, propagation procedures and convergence. Indeed, a chain of microrobots represents the worst case for message broadcasting complexity with $O(n)$, after reconfiguring into a square the complexity will be $O(\sqrt{n})$ in the worst case.

To assess the distributed algorithm performance, we present the simulation results and we compare to former results. Our algorithm is implemented in a real environment simulator called DPRSim, the Dynamic Physical Rendering Simulator.

Outline of the paper. The rest of the paper is organized as follows: Section 4 discusses the model, definitions and some tools. Section 5 discusses the proposed algorithm, it analyzes the complexity of message and memory usage, it shows how to predict the number of movements and shows the generalization of the algorithm. Section 6 details the simulation results. Finally, Section 7 summarizes our conclusions and illustrates our suggestions for future work.

2. Related works

Many terms refer to the concept of self-reconfiguration. In several works on wireless networks the term used is $self-organization$, this term is also used to express the clustering of ad-hoc networks. Also, the self-organization term can be found in protocols for sensors networks to form a sphere or a polygon from a center node [21,32]. Others algorithms for the redeployment of sensor networks are presented in [14,25].

A growing number of research on self-reconfiguration for microrobots using centralized algorithms has been done, among them we find centralized self-assembly algorithms [24]. Other approaches give each node a unique ID and a predefined position in the final structure; see for instance [30]. The drawback of these methods is the centralized paradigm and the need for nodes identification. More distributed approaches include [6,10,27,28]. The authors in [5] have shown how a simulated modular robot (Proteo) can self-configure into useful and emergent morphologies when the individual modules use local sensing and local control rules. In [31] a deterministic distributed algorithm for self-reconfiguration of modular robots from arbitrary to straight chain configuration.

Claytronics, is the name of a project led by Carnegie Mellon University and Intel corporation. In the Claytronics project, microrobots are called Claytronics ATOMS, CATOMS for short.

Many works have already been done within the Claytronics project. In [7,9] the authors propose a metamodel for the reconfiguration of CATOMS starting from an initial configuration to achieve a desired configuration using *creation* and *destruction* primitives. The authors use these two functions to simplify the movement of each CATOM. Another scalable algorithm can be found in [22]. In [2], a scalable protocol for CATOMS self-reconfiguration is proposed, written with the MELD language [1,23] and using the creation and destruction primitives. In all these works, the authors assume that all CATOMS know the correct positions composing the target shape at the beginning of the algorithm and each node is aware of its current position. The first self-reconfiguration without predefined positions of the target shape appears in [15,16,19]. However, these solutions are not parallelized and take longer to achieve the self-organization. In [17], we propose another solution that guarantees the connectivity of the network through the execution time of the algorithm. In [18], we propose a solution that guarantees the connectivity of the network however, this solution is not optimal if the size of the network is not a square root (an integer which is the square of another integer). This new work optimizes the execution time and the energy consumption (number of movements) and deal with all sizes of the networks. A preliminary version of this paper appears in [20].

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