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Building simple formations in large societies of tiny mobile robots ☆

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Abstract

We envision that in the future lots of tasks that are handled nowadays by few but complex mobile robots will be performed by huge swarms of tiny robots. This way the system becomes more robust against single failures and cheaper, since the robots can be very simple. As a prerequisite, the robots have to be able to form given formations in order to organise their work. We review new strategies that perform the task of building a simple line with robots that are limited to see only their direct surrounding. As energy is the main limiting factor, we analyse how the two main energy consumers (energy for sensing and energy for motion) are affected by our algorithms.

1. Introduction

Nowadays more and more tasks are handled by autonomic mobile robotic systems. So far, most of these systems consist of very complex robots that are expensive and error-prone. We envision a development towards large systems of tiny, simple, cheap robots. Such systems of robots cannot be centrally controlled or optimised. Instead, they have to work in a distributed fashion, where each robots bases its decision on very limited information about its local environment. The challenge arising in this context is to take decisions such that the local strategies of the robots result in a globally desired behaviour of the whole system. If such strategies can be designed, they have several advantages over solutions based on few complex robots: the cost will decrease because of the simplicity of the robots; the systems will be much more robust against failures, because the solution does not depend critically on single entities; strategies designed for such systems will often work well also in dynamic environments (e.g., if the tiny robots are moved by wind or mobile obstacles change the environment). In order to be able to solve complex tasks, as a prerequisite, the tiny robots need to be able to organise themselves into simple formations. One of the simplest formations one can think of is a line. Therefore, in the remainder of this work, we will present approaches how to form lines under the major constraint of limited information and we will review recent results.

2. Problem description

We study the problem of building a short chain of n tiny robots between two fixed *stations*. We assume that the tiny robots in between are mobile and already organised in a chain. However, this chain can be arbitrary long and winding. We want to transform this chain into a short one, i.e. one which is close to the *straight* line connecting the stations. The robots only know their predecessor and their successor in the chain. Furthermore, neighbouring robots are within a limited viewing range - normalised to 1 - of each other. All our strategies guarantee that the neighbouring robots remain within this viewing range. Note that it naturally follows that the length of the chain is at most n.

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In order to formulate and analyse our strategies, we model time in discrete synchronous steps. In each step, all robots simultaneously observe the positions of their two neighbours. Based on their relative positions, they compute the next position to which they want to move. Subsequently they move to the calculated position. Then the next time step starts with the same procedure. Note that the position of the neighbouring robots change during the time step.

Our goal is to define strategies that transform any given chain as described above into a shortest one without breaking the connectedness of the chain. Furthermore we want to achieve this goal while spending as little energy as possible. This is of major importance since energy is a rare resource in such battery-driven mobile systems.

The two main energy consumers in our setting are the energy needed for sensing the environment and for travelling. The energy spent for sensing is proportional to the number of time steps needed, since there is exactly one sense operation per time step. The energy for travelling is proportional to the total distance travelled by a robot.

3. Our approach

Generally, our work on local strategies for robotic formation problems aims at designing strategies and giving rigorous mathematical proofs for their correctness and quality. Correctness means that the desired formation is reached or approximated well in finite time. Quality can be measured in various ways, here we focus on the energy measures mentioned above. The results typically are described by bounds on the amount of energy needed as a function in the number n of robots, taking the worst case over all configurations of the initial chain.

4. Strategies and Results

The strategies we consider are usually easy to state, easy to implement and easy to be performed by the tiny robots. For instance, we do not require that they have a memory. This has the additional advantage, that transient failures can be neglected. After a failure, the new chain can be considered as a new input and all our guarantees hold once again.

We consider variants of the *Go-To-The-Middle strategy* [2]. Here, all robots simultaneously compute the midpoint between their two neighbours and subsequently move there. We measure the number of discrete time steps that are needed, until all robots are within a given constant distance to their final destination on the line. We prove that, for n robots, this takes at most a number of steps that is proportional to $n^2 \log n$. The proof of this time bound is based on insights that relate progress of the strategy to the so-called mixing time of certain classes of Markov chains. Furthermore, we provide an initial input where the Go-To-The-Middle strategy actually needs at least a number of steps proportional to $n^2 \log n$ [3]. Thus, our runtime bound is tight up to constant factors.

We can also show that the distance travelled is proportional to n^2 [1]. Once again we also present a start configuration for which this actually happens. On the other hand, it is easily seen that, using an optimal, global strategy, a distance of at least n has to be travelled. Intuitively, the distance travelled when using Go-To-The-Middle strategy is large, because we sense the positions of the neighbours not often enough.

This insight leads us to the idea to modify the strategy as follows: We let the robots only move a fraction of δ towards the middle of the neighbours, where δ is parameter that can be adjusted [1]. Of course, the results now depend on the parameter δ: We can prove that the new strategy needs at most proportional to $n^2 \log n + \frac{n}{\delta}$ many steps and travels a distance of at most proportional to $\delta n^2 + n$. For both results we have examples that show that the analysis is asymptotically tight. Thus, choosing $\delta = \frac{1}{n}$ is asymptotically optimal for both energy consumers. This is a rather surprising fact, since we do not need a good compromise, but can optimise both requirements at the same time.

As a final remark we note that our *Hopper strategy* only needs proportional to n steps and travelled distance [4]. But this strategy needs a more complex synchonisation (a robots starts its round as soon as its predecessor has finished its one) and a more complex strategy based on a three-fold case analysis.

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