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Efficient reconfiguration of lattice-based modular robots



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ABSTRACT

Modular robots consist of many identical *units* (or *atoms*) that can attach together and perform local motions. By combining such motions, one can achieve a reconfiguration of the global shape of a robot. The term *modular* comes from the idea of grouping together a fixed number of atoms into a *metamodule*, which behaves as a larger individual component. Recently, a fair amount of research has focused on algorithms for universal reconfiguration using *Crystalline* and *Telecube* metamodules, which use expanding/contracting cubical atoms.

From an algorithmic perspective, this work has achieved some of the best asymptotic reconfiguration times under a variety of different physical models. In this paper we show that these results extend to other types of modular robots, thus establishing improved upper bounds on their reconfiguration times. We describe a generic class of modular robots, and we prove that any robot meeting the generic class requirements can simulate the operation of a Crystalline atom by forming a six-arm structure. Previous reconfiguration bounds thus transfer automatically by substituting the six-arm structures for the Crystalline atoms. We also discuss four prototyped robots that satisfy the generic class requirements: M-TRAN, SuperBot, Molecule, and RoomBot.

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1. Introduction

A self-reconfiguring modular robot consists of a large number of independent *units*, or *atoms*, that can arrange themselves into a structure best suited for a given environment or task. For example, a robot may reconfigure into a thin linear shape to facilitate passage through a narrow tunnel, transform into an emergency structure such as a bridge, or surround and manipulate objects. Because modular robots comprise groups of identical atoms, they are also more easily repaired, by replacing damaged atoms with functional ones. Such robots are well-suited for working in unknown and remote environments.

A variety of atom types have been designed and prototyped in the robotics community, differing in shape and in the operations they perform. We focus here on lattice-based modular robots in which atoms are arranged on a regular grid. Examples of prototyped atoms include Crystalline [4], M-TRAN [11], Molecule [25], SuperBot [19,6], and RoomBot [20].

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For a comprehensive list, see [14,23]. Atoms are equipped with mechanisms that allow them to attach/detach to/from neighboring atoms, and motion is typically achieved through the activation of one or more revolute or prismatic joints.

One of the algorithmic challenges for these modular systems is to determine efficient sequences of atom operations that transform a robot from one configuration to another. A typical requirement is that the atoms maintain connectivity at all times. As observed in [15], difficulties can arise from blocking constraints, such as when an atom is unable to directly move into an adjacent empty position of the lattice because it is blocked by tightly packed neighboring atoms. As a consequence of such constraints, it is possible that for certain configurations of a robot, no atom can move. This was demonstrated in [15] for hexagonal atoms. Certain atom types require a sufficient number of neighboring atoms to move non-trivially. For example, a $1 \times n$ linear configuration of Crystalline atoms is not universally reconfigurable.

To address some of these difficulties, the concept of *metamodules* was introduced in [15,10]. A metamodule is a small collection of atoms that behave as a single unit. Rather than specifying robots at the atom level, they are specified in terms of metamodules on a lower resolution lattice. These atoms combine to produce a synergistic effect, so that a metamodule has more freedom of movement than any individual atom. It is often the case that metamodules are sparsely constructed, which enables them to pass very close to (or in some sense, through) each other, without the type of blocking constraints mentioned previously. Throughout this paper, we will refer to robots that have $\Theta(n)$ atoms and metamodules. That is, we are only interested in metamodules consisting of a constant number of atoms.

Nguyen et al. [15] proposed metamodules consisting of 36 hexagonal atoms arranged along the boundary of a larger hexagonal region with an empty interior. They provided an algorithm to transform between any two “fat” robot configurations in $O(n)$ time. Prevas et al. [16] used metamodules consisting of 8 I-Cube atoms and 16 links to achieve an $O(n^2)$ time universal reconfiguration algorithm. Recently, there has been a fair amount of algorithmic research on universal reconfiguration using metamodules of expanding/contracting cubical atoms. The two main prototypes considered have been Crystalline and Telecube atoms, which are similar enough that we will henceforth refer only to the former. Crystalline metamodules are $k \times k \times k$ arrangements of atoms, where k is a small constant that varies depending on the situation. Specifically, the size of a metamodule depends on various factors, including the assumed physical capabilities of each atom.

In the weakest and most realistic physical model, Crystalline atoms have constant strength (i.e., they can push and pull a constant number of other atoms when expanding and contracting) and the maximum speed they can reach during reconfiguration is also bounded by a constant. Early reconfiguration algorithms that used this model include the “melt-grow” algorithm of Rus and Vona [18], and that of Vassilvitskii et al. [21], both of which reconfigure in $O(n^2)$ time. This was improved in [1] to linear time using metamodules of $2 \times 2 \times 2$ atoms, with a total of $O(n^2)$ atom operations (counting operations performed in parallel). Both bounds were shown to be worst-case optimal. The linear time algorithm also requires only constant memory per atom and local communication between atoms.

More physically capable atoms naturally allow for faster reconfiguration algorithms. For instance, the total number of atom operations can be reduced to $O(n)$ in a model that assumes that atoms have linear strength [2]. This means that atoms can push and pull up to n other atoms when contracting and expanding. When constant strength is assumed but velocities are allowed to build up over time, reconfiguration is possible in $O(\sqrt{n})$ time in 2D, using 4×4 metamodules and the third dimension as an intermediate [17].

In the most physically capable model where atoms have linear strength and velocities can be instantly linear, any 2D reconfiguration is possible in $O(\log n)$ time using $O(n \log n)$ total operations [3]; the algorithm uses metamodules of size 4×4 , but it is claimed that it can be reduced to 2×2 . A straightforward (yet unpublished) extension of this result achieves the same asymptotic bound in 3D, using larger but still constant-sized cube-shaped metamodules.

To our knowledge, similar asymptotic bounds on universal reconfiguration for other lattice-based modular robots are not yet known. In this paper, we extend the Crystalline reconfiguration results to other lattice-based modular robots. Specifically, we describe a generic class of modular robots, and we prove that any robot meeting the generic class requirements can simulate the operation of a Crystalline atom by forming a structure called a 6-arm. We also discuss four prototyped robots that meet the generic class requirements: M-TRAN, SuperBot, Molecube, and RoomBot. By replacing Crystalline atoms with 6-arms in the $k \times k \times k$ metamodules used by existing Crystalline algorithms, the reconfiguration results immediately apply. Thus as in the previous work, reconfiguration assumes (and exploits) the existence of specifically constructed metamodules, and the reconfiguration bounds apply to robots composed of these metamodules. From an algorithmic perspective, the asymptotic universal reconfiguration times achieved here via the Crystalline algorithms using the 6-arm construction are the most efficient known for the M-TRAN, SuperBot, Molecube, and RoomBot robots.

The term “efficient” in this paper refers to the asymptotic time complexity of the reconfiguration algorithms. We point out that cost and physical limitations of prototyped atoms make the work here a theoretical contribution, rather than a practical one. The number of atoms in the 6-arm is 58, which renders the 6-arm construction and its operation impractical with existing hardware implementations of prototyped atoms. Our goal has been to establish that several prototypes have no fundamental geometric disadvantages compared to Crystalline atoms (metamodules). The limiting effects of torque, motor abilities, and gravity are not of primary concern here.

Our aim has been to establish a global simulation structure. The 6-arm metamodule is a general construction that can be applied to a variety of atom types. One would naturally expect that customizing a metamodule for each type of atom would lead to smaller constructions. For example, it has been shown that an 8 atom customized M-TRAN metamodule can simulate a 2D Crystalline atom [12].

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