A new meta-module for efficient robot reconfiguration*

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Abstract

We present a robust and compact meta-module of M-TRAN and other similar robots that is able to perform the expand/contract operations of Crystalline and Telecube robots, based on the rotational degrees of freedom of M-TRAN units. Our meta-modules also perform the scrunch/relax and transfer operations of Crystalline and Telecube meta-modules. These results make it possible to apply efficient geometric reconfiguration algorithms to this type of robots.

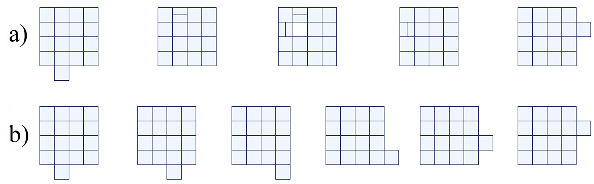

Figure 1: Different reconfiguration strategies. In both cases, the leftmost configuration is the starting one, and the rightmost is the target one. a) Tunnelling algorithm for expandable and contractible modules. b) Surface algorithm.

1 Introduction

Modular self-reconfigurable robots are connected sets of units that can change their connectivity, varying the shape of the robot. Thus, these systems can modify their morphology (reconfigure) to better suit different tasks and environments and to self-repair. This makes them more versatile and robust than fixed-shape unique-purpose robots.

They can be classified according to different criteria: architecture and topology, connections, degrees of freedom, propulsion method, etc. We are interested in robots whose units are able to expand and contract since this property can be exploited by reconfiguration algorithms. As can be seen in Figure 1a, for this kind of units movements interior to the robot configuration are allowed, leading to tunneling reconfiguration strategies, in which modules travel through the volume of the robot. Figure 1b shows how the same reconfiguration is achieved by means of a surface strategy, i.e., by moving the units along the boundary of the configuration.

Physical prototypes of self-reconfiguring systems with square or cubic units that can can expand and contract by a factor of two in each of its dimensions are Crystalline robots [9] in two dimensions and Telecube [12] in three dimensions.

Several tunneling algorithms for universal reconfiguration have been proposed for Crystalline and Telecube robots. In all of them the units are grouped into meta-modules of at least $2 \times 2(\times 2)$ units. The *melt-grow* [8] is a centralized algorithm which reconfigures any connected robot of n units in $O(n^2)$ moves and steps. The *Pac-Man* algorithm [5] and the algorithm in [13] use $O(n^2)$ parallel steps. Maintaining the assumptions of constant velocity and strength and using meta-modules of $2 \times 2(\times 2)$ units, *in-place* reconfiguration (space requirement is just the union of the the source and target configurations) is possible in linear time [2]. The total number of unit moves is $O(n^2)$, which is optimal in this setting. Requiring modules to have linear strength, i.e., to be able to pull or push a linear number of other modules, the total number of unit moves can be reduced to $O(n)$ [3]. With this force requirements and allowing velocities to build up over time, reconfiguration is possible in $O(\log n)$ parallel steps and $O(n \log n)$ total moves [4].

Many current modular robots prototypes have other very convenient properties but cannot expand and contract. We would like to apply the previously described algorithms also to some of these robots by constructing meta-modules with their units, which cannot expand and contract, such that the whole meta-module can.

One of the most interesting robotic systems developed so far is the M-TRAN series, from M-TRAN I to M-TRAN III [6]. On one hand, its units (Figure 2) can be connected in a string or tree topology which allows for continuous movement. This makes M-TRAN suitable for a wide range of tasks. On the other hand, the blocks constituting its units can be arranged in a cubic grid. In this lattice architecture reconfiguration is simpler.

For these reasons, there has been interest in design-

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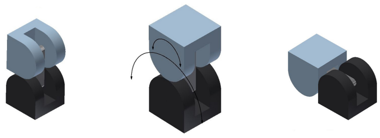

Figure 2: An M-TRAN unit.

ing meta-modules of M-TRAN units that can expand and contract. Murata and Kurokawa present in [7] a small and compact meta-module, but it can only expand and contract in 2 dimensions. For 3D, the only such meta-module that we are aware of is that of Aloupis et al. [1]. Their meta-module is also valid for Molecube units [14]. However, the meta-module of [1] is formed by 58 units and the side length of its minimum axis-aligned bounding cube when expanded is 32 units. In addition, it is much less compact than the one by Murata and Kurokawa, making it less robust.

We would be interested in a more realistic meta-module, both in size and number of modules.

Results Restricting ourselves to M-TRAN, in Section 2 we present a more robust and compact meta-module that is able to simulate the operations performed by Crystalline and Telecube units. The meta-module we propose is also valid for SuperBot [11] and iMobot [10]. Moreover, since the meta-modules of expandable and contractible units required in the algorithms would lead to meta-meta-modules of M-TRAN units, in Section 3 we show that these meta-meta-modules can be avoided.

2 A smaller and more robust meta-module

M-TRAN units (Figure 2) consist of two linked semi-cylindrical cubes. We refer to these semi-cylindrical cubes as *blocks*. Each block has a gender (male/female) and connectors (different for the two genders) on its three flat surfaces. Two units can be attached by flat surfaces of different gender, in any of the four possible relative orientations.

The units have two degrees of freedom: each semi-cylindrical block can rotate from $-90°$ to $90°$ with respect to the link joining both blocks (Figure 2).

In the remaining of this section we describe how M-TRAN units can be combined into a meta-module that is able to expand and contract.

Our meta-module, illustrated in Figure 3, consists of 6 *arms*, aligned in three directions that are parallel to the x, y and z axes.

Each arm is implemented using a *2-unit chain*: two units attached at square flat faces and with the direction of their links aligned, as shown in Figure 4. The key property of 2-unit chains is that the rotation of the blocks within the units allows them to contract an expand, while preserving potential connections.

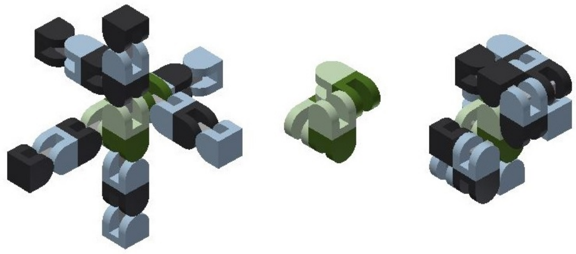

Figure 3: Our M-TRAN meta-module. Left: all arms expanded. Center: central blocks. Right: all arms contracted.

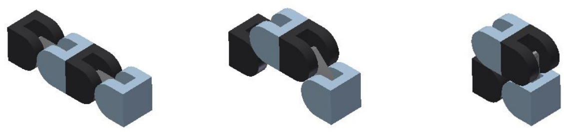

Figure 4: The 2-unit chain is able to contract while maintaining its potential connections at both ends.

Lemma 1 *The 2-unit chain can be contracted. During this operation its two extremal blocks stay aligned and keep their orientation.*

Proof. The contraction operation is shown in Figure 4. Its realization is allowed by the two rotational degrees of freedom and the semicylindrical shape of the blocks. It is easy to see that this operation does not change neither alignment nor the orientation of the extremal blocks of the chain. □

The pairs of arms of the meta-module that are oriented in the same direction are connected to each other, resulting in a 4-unit chain whose blocks are all aligned. However, the linkages of the two connected arms differ in their orientation (see Figure 5 left). We call the blocks connecting the two arms *central*. The end blocks of a 4-unit chain are called *tips*.

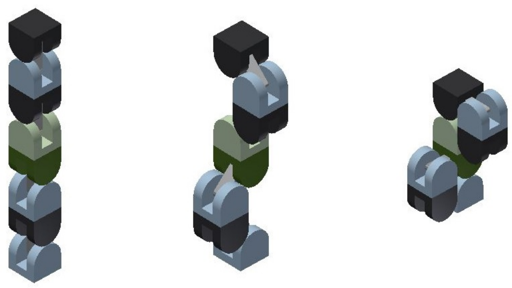

Figure 5: Left: connecting two arms into a 4-unit chain. The central blocks are highlighted in green. Right: the compression movement.

The six arms of the meta-module form three 4-unit chains, one for each of the x, y and z directions, attached through their central blocks at their semicircular faces.

Since the linkages of the two arms forming a 4-unit chain have different directions, their contraction and expansion movement takes place on two orthogonal planes, as illustrated in Figure 5 right.

The meta-module can contract or expand each arm independently while keeping the six central blocks still. An important property of the meta-module is that the expansion or contraction of an arm can never interfere with another arm of the same meta-module.

Lemma 2 *No self-intersection is produced when expanding or contracting any of the six arms of the meta-module.*

Proof. Consider the minimum axis-aligned cube containing the expanded meta-module and decompose it into eight octants. It is easy to see that each expanded arm is contained in a different octant. The plane on which the contraction of an arm occurs always has a region in the corresponding octant. Therefore, when we contract an arm, we can always use the octant that is exclusive to that arm. This guarantees that collisions cannot occur. □

Lemma 3 *During the expansion and contraction of any subset of arms of a meta-module the structure remains connected.*

Proof. While expanding and contracting any arm, the central blocks remain immobile. These six blocks maintain the meta-module connected at all times. Moreover, connectivity with neighboring meta-modules is preserved: if the tip of an arm is attached to the tip of another meta-module arm, Lemma 1 guarantees that this attachment can be maintained during expansion and contraction. □

Theorem 4 *The meta-module can perform the Crystalline and Telecube unit operations: expand, contract, attach and detach.*

Proof. From the previous lemmas we conclude that, in any direction, the length of the meta-module can be reduced by half (when expanded arms are contracted) or doubled (when contracted arms are expanded) in any of the x, y and z directions. This can be done while preserving connectivity (Lemma 3) and avoiding collisions (Lemma 2). □

The meta-module we have presented uses 12 M-TRAN units. When expanded, its length is 8 units. Thus, the number of units is significantly reduced with respect to the 58-units meta-module presented in [1] and its size is scaled down to half.

Furthermore, robustness is also improved over the previous meta-module: when contracted, our meta-module has only two corner joints per arm, as opposed to the four used in previous work, and leaves no gaps, making it much more compact.

3 Avoiding meta-meta-modules

By Theorem 4, we can apply the algorithms in [8, 5, 13, 2] for Crystalline and Telecube units to our meta-module. These algorithms, in turn, use meta-modules of Crystalline or Telecube units that are able to perform the following operations:

Scrunch and *Relax*: compressing two connected meta-modules so that both occupy the same single lattice cell, and the reciprocal operation. See Figure 6a.

Transfer: a compression in a meta-module is transferred to an adjacent lattice cell whose meta-module is not compressed. See Figure 6b.

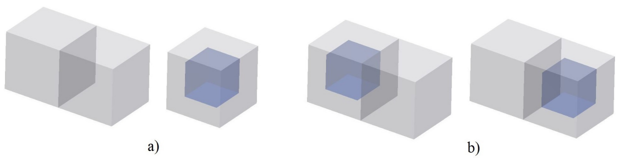

Figure 6: Crystalline and Telecube meta-module operations. a) Scrunch and Relax. b) Transfer.

In the previous section we showed that our meta-module is able to perform the Crystalline and Telecube unit operations. In this section we show that meta-meta-modules of M-TRAN units are not required since our meta-module is also able to simulate the scrunch/relax and transfer operations. This decreases the resolution of the configurations that we can handle, both in size and number of units.

Figure 7 illustrates two adjacent meta-modules before and after a scrunch/relax operation. In a scrunch operation one of the meta-modules stays still, guaranteeing the connectivity of the overall structure. The other meta-module adopts a position that we call *canonical*, and has the following properties: *(i)* the 4-unit chains of the moving meta-module are parallel to those of the still meta-module, and they are all connected at their central blocks; *(ii)* the symmetry of the resulting configuration allows to perform a relax operation on the moving meta-module to place it in any of the six adjacent lattice cells.

In a transfer operation two adjacent meta-modules stay still, while the other moves from the canonical position attached to one of the still meta-modules to the canonical position attached to the other.

The low density of the configuration with two meta-modules in the same bounding box, as shown at the bottom of Figure 7, allows performing the scrunch/relax and transfer operations. Their actual implementation is rather involved. It comprises 57 independent moves of the six 2-unit chains of the moving meta-module for the scrunch operation and 69 for the transfer operation.

This leads to the following result, whose proof we omit due to space limitations.

Theorem 5 *The meta-module can perform the Crystalline and Telecube meta-module operations* scrunch/relax *and* transfer.

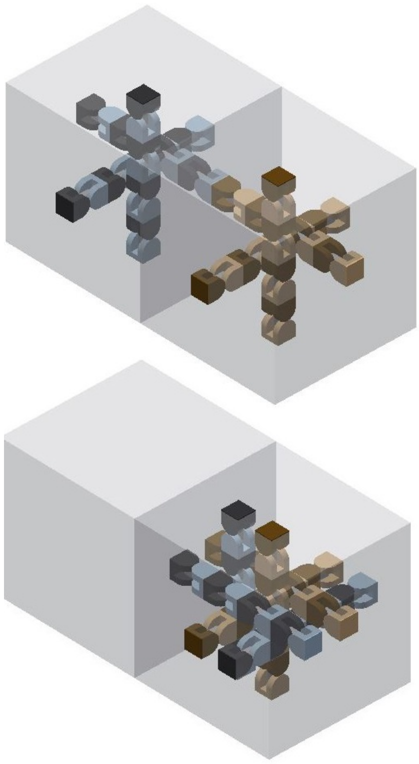

Figure 7: The scrunch/relax operation. Notice the canonical position of the blue meta-module in the bottom figure.

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