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A unit-compressible modular robotic system and its self-configuration strategy using meta-module

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ABSTRACT

Many modular robots can be configured together to constitute a system. However, it is yet difficult to accomplish the configuration tasks by modules themselves since there are many constraints in a system. Introducing the meta-module into control strategy may realize the self-configuration by reducing constraints. Based on this idea, this paper presents a novel self-configuration strategy for a unit-compressible modular robotic system. First, a hardware system called M-Lattice that allows to construct a planar hexagonal lattice of robots is introduced. By using a special motion mode to move modules, this system is able to reduce the local constraints. A kinematics analysis and two prototype robots are presented to demonstrate this ability. Then, a novel self-configuration strategy based on the concept of meta-module is proposed. The meta-module is a small group of basic modules that work cooperatively as one intelligent unit. Every meta-module can self-configure in the system by itself and the global constraints are effectively reduced at the same time. The overall performance of the proposed strategy is evaluated with simulations and the simulation results show that it has a fine performance in scalability as well as robustness.

1. Introduction

Over recent years, applications of modular robotic system (MRS) have increasingly drawn the attentions of robotics and control communities. The MRS has some advantages, such as the good modularity as well as excellent flexibility. And it can be geometrically classified into three types: the chain-type, the lattice-type, and the mobile-type [1]. The chain-type MRS [2–4] arranges modules in a string or tree structure and holds great locomotive ability. Modules of the lattice-type MRS can be cubic [5–7], sphere [8], cylindrical [9] and also other forms of modules [10,11]. These modules are arranged in some special structures and generally have more than two connectors so that they are able to move in the system with the help of other modules. Modules of the mobile-type MRS [12–14] are not only able to work independently but also can be configured together to accomplish various tasks. Furthermore, there are several kinds of hybrid-type MRS [15–17] which can work in different ways with different configurations.

Especially, the MRS can constitute various configurations based on the diverse combinations of modules and the control strategy plays a key role in these works. In a centralized control strategy, a central controller compares target configuration with current configuration in real time and then informs some modules to move into the calculated target locations. However, as the centralized control strategy may get a bad performance while the MRS becomes larger, the distributed control strategy [18–20] where all modules operate based on their own decisions attracts more attentions.

The self-reconfiguration has great reference meaning to the self-configuration. Kurokawa et al. [21] presented both the centralized and distributed self-reconfiguration experiments of M-TRAN III MRS. And in the domain of hexagonal lattice configuration, Naz et al. [9] presented a self-reconfiguration algorithm of rolling cylindrical modules arranged in a 2D vertical hexagonal lattice. The authors in [22,23] proposed a parallel as well as distributed self-reconfiguration algorithm of their modules from a chain configuration to an arbitrary shape that satisfies a simple admissibility condition in a hexagonal lattice. And in [24,25], Lakhlef et al. proposed the distributed algorithms that manage to construct square shapes with spherical modules arranged in a 2D hexagonal lattice. In [26], Hurtado et al. presented the first known reconfiguration algorithm that applies in a general setting to a wide variety of particular MRS. It is a distributed algorithm and holds for both square and hexagonal lattice-based 2D systems.

The self-configuration tasks are difficult for modules since there are many constraints throughout the configuration tasks. The goal of self-configuration is to build a mechanical structure from nothing while it

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is accomplished by modules themselves. This work is a little different from the self-reconfiguration tasks where the MRS is configured from one structure to another [27]. And we think that for a MRS the self-configuration is the basis of self-reconfiguration. Once we obtain the basic structure after self-configuration, other things can be placed and built based on it. We can build shelters for disaster relief, construct working platforms in deep sea water, develop floating bridges over the river, and also operate the self-reconfiguration tasks.

Method of using the MRS to perform the self-configuration tasks was first proposed in [28]. In their work, the configuration tasks were carried out by two different kinds of robots: the structure modules and the assembler robots. However, work efficiency of such heterogeneous MRS is likely to suffer from the round-trips between the target locations and module supply area. Therefore, the homogeneous MRS [29,30] is proposed to benefit from the homogeneity of modules so that it has a better performance of efficiency as well as robustness. [27,31–33] have studied several homogeneous MRSs which are used to carry out the self-configuration or self-reconfiguration tasks. And in this paper, an improved MRS called M-Lattice whose modules are identical and homogeneous is introduced first. M-Lattice MRS acts as a key part of the solar power satellite (SPS) [34], which is placed in outer space, converts the solar radiations into electrical energy, and then transmits the energy to Earth via the electromagnetic energy beams. Fig. 1 shows the representation of the SPS with our M-Lattice MRS.

Because of the special space environment, modular robots are required to be stored in a space rocket. After launched into space, they are self-configured to form a MRS. Afterwards, the SPS starts while the MRS works as a solar cell array to receive and convert the solar radiations. Such design can make the SPS have a small spatial volume with a large expanded surface area, so that it is able to receive more solar radiations with the limited number of modules. Moreover, the system connectivity is especially underlined throughout the self-configuration tasks, because the MRS may lose control of the disconnected parts in a weightless environment. This character is quite different from a common self-configuration task carried out at ground level where the disconnected parts would not move because of the gravity and friction.

Therefore, to expand the application area of the MRS and perform the self-configuration tasks in various environments, the constraints in MRS should be investigated in detail. Several studies [35–37] had used meta-modules to reduce constraints in the self-configuration tasks of MRS. The meta-module is a small group of basic modules. White and Yim [38] used XBot to extend the motion primitives and also proved that the XBot meta-modules are able to reach any configurations by using their limited motion primitives. Nguyen et al. [39] argued about a skeletal meta-module which is not only able to collapse inside another meta-module, but also to come out and then form a meta-module again.

In this paper, the constraints in MRS are reduced from two aspects. At a mechatronic level, M-Lattice modular robot is designed to be unit-compressible with telescopic DOFs, so that the local constraints can be reduced by using a special motion mode. And at a control level, a novel self-configuration strategy for the M-Lattice MRS is proposed where every single meta-module is taken as a motion unit. It moves in the system, occupies the suitable vacancies and then turns into a part of system at last. The proposed strategy can maintain the system connectivity to reduce the global constraints and it also has good performance in both scalability and robustness.

The remainder of this paper is organized as follows. In Section 2, the structure of M-Lattice modular robot and its special motion mode are described. In Section 3, we present the kinematics analysis and demonstrate a hardware experiment of two prototype robots. In Section 4, the novel meta-module self-configuration strategy for the M-Lattice MRS is presented. And the overall performance of the proposed strategy is evaluated by simulations in Section 5. In Section 6, problems raised from the simulation results and the future works are discussed. Finally, this paper is concluded in Section 7.

2. The M-Lattice MRS

2.1. The SPS with M-Lattice MRS

Fig. 1 is the representation of the SPS with our M-Lattice MRS. Many M-Lattice modules equipped with solar panels are configured together to constitute a large 2-D MRS that works as a solar cell array in outer space to convert the solar radiations into electrical energy. The satellite body collects the electrical energy and then transmits it to Earth via the electromagnetic energy beams. Moreover, the engines in satellite body enable the SPS to move in a weightless environment and the size of MRS could be much larger.

2.2. Constraints

It is challenging to deal with the constraints in MRS. In a typical MRS, the constraints can be classified into two types: the local constraints and the global constraints.

Fig. 2(a) is an example of the local constraints. Locations of C, E, F, G and H should be empty if a square module wants to move from B to D while rotating around A. Otherwise, there is collision happening between two neighbors. We can see that the local constraints are mainly determined by the module's structure as well as its motion mode. Therefore, besides of the reliability of connectors, module's structure should reduce the local constraints as much as possible.

On the other hand, Fig. 2(b) is an example of the global constraints. Because the system may be separated into several parts, module A and B cannot move into D and C, respectively. The global constraints are very important for the module transportation during the self-configuration tasks and it will be later discussed in Section 4.

2.3. M-Lattice modular robot

Inspired by the design of Crystal [40] which is a unit-compressible modular robot, we design the M-Lattice modular robot as a center frame

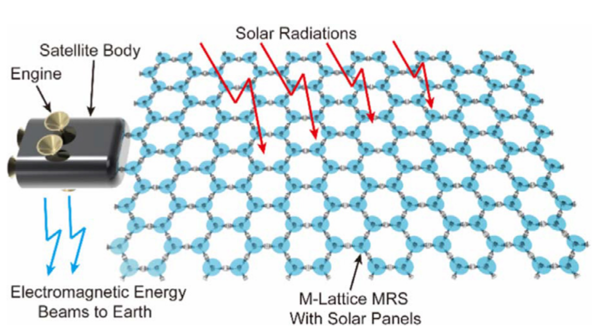

Fig. 1. The SPS with M-Lattice MRS.

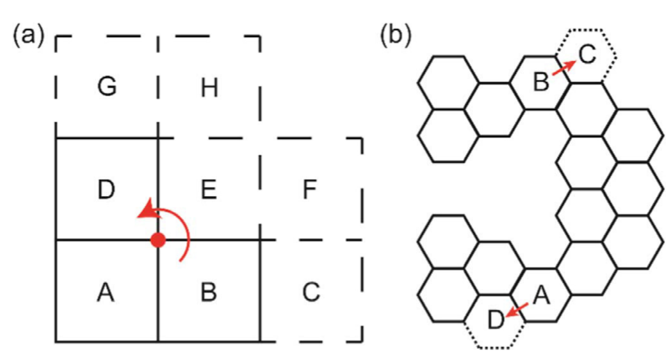

Fig. 2. (a) The local constraints, and (b) the global constraints.