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An underactuated self-reconfigurable robot and the reconfiguration evolution

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ABSTRACT

Biological cells and tissues have diversified behaviors, which are supported by active tissues and passive tissues. Inspired by this, an underactuated self-reconfigurable robot was designed with passive joints and active joints. The inclusion of passive joints can offer benefits not only on cost but also on functionality. This paper presents the architecture of the underactuated self-reconfigurable robot, a computational model of reconfiguration planning and reconfiguration scheduling. An experiment is given to demonstrate the reconfiguration process.

1. Introduction

Self-reconfigurable robots are robots that are composed of a set of modules that can change their configuration. These robots are used in unknown environments where robots may be required to change their configurations to meet the demands of a specific task. Particularly in planetary exploration, the robots are desirable to be cost-effective, for example, to employ a single robot that is capable of performing different tasks such as assembling and carrying objects and recovering its original function after partial damage.

Most self-reconfigurable robotic systems are homogeneous systems that consist of identical active modules which encapsulate actuators, connection systems, sensors, controllers, and effectors [1–6]. In contrast, there are fewer studies on heterogeneous self-reconfigurable robots [7–9]. Odin robot [7] consists of active links and active joints, in which the active links provide power and structure functionalities, and the active joints transfer the power and information between any adjacent links. ICubes robot [8] uses a manipulator composed of rigid links and active joints to move passive cubes around. Morpho robot [9] consists of passive modules and active modules and connectors, in which the passive modules function as linear joints, and they are specified for contraction and extension only. In short, heterogeneous systems that take advantage of passive joints and passive links reduce energy consumption for the actuators and increase the functionalities. This paper proposes an underactuated self-reconfigurable robot that has active joints and passive joints.

The main contribution of this paper is a computational model of reconfiguration of an underactuated self-reconfigurable robot with a novel docking system. First, we analyze the architecture of the underactuated self-reconfigurable robot and the

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docking system. Second, we give a computational model of the self-reconfiguration problem for the proposed architecture. Third, a design case is given to demonstrate how the proposed model work.

This paper is organized as follows. Section 2 reviews related work on docking systems and self-reconfiguration problem. Section 3 describes the design of docking system and the reconfiguration process. Section 4 presents the model of self-reconfiguration. Section 5 describes an experimental underactuated self-reconfigurable robot to demonstrate the self-reconfiguration process, and Section 6 gives conclusions and future work.

2. Related work

2.1. Docking systems

To realize self-reconfigurability, an effective connection system for locking and releasing modules is crucial. Numerous connection systems for self-reconfigurable robots [10–12] or reconfigurable robots [13–15] have been developed The most common connections are mechanical connections and magnetic connections. Mechanical docking system enables strong connections. A motor or other form of actuating element, such as a shape memory alloy (SMA), is used to mate posts with latches, or mate holes with grooves. PolyBot robot [2] and CONRO robot [3,16] use peg-and-latch connection systems in which a peg male part is inserted into the female part, and then a latch falls to lock the connection, and the connection is released when the shape memory actuators (SMAs) are heated. Crystalline robot [17] uses rack-and-pinion mechanism to actuate the expansion and contraction of the faces. Each face of the module has part of a connection mechanism. Two out of the four faces have active latches mechanisms, and the other two have passive channels. The module with faces that actively make the connection is called active, and the one that allows themselves to be connected is called passive. Similarly, ICubes robot [18] uses a key-lock connection mechanism, where the key inserts into a hole and rotates, and then is fixed into the locked position. The detachment action is carried out in reverse order. Another design is to change the peg or key into an active hook, and the robot uses a hook mechanism to achieve connection and disconnection, such as ATRON robot [19].

In magnetic connection systems, two surfaces are engaged by the attractive force between two magnets. In M-TRAN robot [20], each module's faces have polarity, and two connected faces have different polarity to connect. Disconnection of two surfaces is achieved by using SMA coils that, when heated, apply a strong pulling force to overcome the strength of the magnets. Another method of disconnecting two permanent magnet connectors, as applied to the SMORES platform [21], is to insert a docking key system into the connected modules' docking port, holding it in place, while rotating its connector to separate the two magnets. This disconnection is much faster than the SMA approach. The locking actions for magnetic connection systems are relatively simple but the connection is not strong, and it may be disconnected by accident. As well, it consumes a relatively large amount of energy and needs an actuation mechanism for detachment, which is usually more complex and increases the weight and energy consumption.

Another issue is that most connection systems have an independent power source for connection and disconnection only, which is designed at the cost of size, weight, and energy consumption, such as the mechanical connection systems and magnetic connection systems. To overcome these disadvantages, this paper presents a novel key-lock-based docking system. Unlike the key-lock connection system in ICubes robot [18] that have only one locked position, the "key" of our docking system can have two statuses: (1) the "key" has relative motion with the lock, thus forming a passive joint; (2) the "key" can be locked at different positions in the lock. Since there are active joints, passive joints and links, and all modules can connect with each other to achieve configuration changes, this robot is called an underactuated self-reconfigurable robot. The passive joints may be designed in a robot to reduce the robot's weight, cost, or energy consumption, or an active joint becomes a passive joint as a result of an actuator failure. It is noted that, in this robot, the reconfiguration (i.e., connections and disconnections) share the same motor with the locomotion, rather than using a separate drive, which is also a good way to reduce the cost. As there is no separate actuator for reconfiguration, the disconnection of two modules was achieved by the cooperation of all actuators in a loop. The inclusion of passive joints increases the degree of freedom (DOF) of the chain, thus increases the flexibility of disconnection.

2.2. Self-reconfiguration planning and scheduling

The self-reconfiguration problem includes reconfiguration planning and reconfiguration scheduling, which is defined by the initial configuration and goal configuration. Reconfiguration planning is to find a sequence of moves from an initial configuration to a goal configuration. Reconfiguration scheduling is the realization and implementation of a successful reconfiguration planning, including the coordination or control of movements of the modules. It is noted that the goal configuration search is driven by a specific task, and the goal configuration search for the underactuated self-reconfigurable robot can be referred to our previous work in [22].

For the problem of reconfiguration planning, the main idea is heuristic-based. Examples of the work for lattice-type self-reconfigurable robots can be seen in [23] and [24–28]. It is noted that in lattice-type robots, the position of each module's position is specified by a unique 2D or 3D coordinates, and the configuration space is relatively small. However, the configuration space becomes much larger in chain-type robots. Only a few studies on chain-type robots are reported in the current literature. See, for example, [29–32]. Further, the study in [32] proved that finding the optimal reconfiguration planning problem of finding the least number of reconfiguration steps to transform from a start configuration to a goal configuration