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ModRED: Hardware design and reconfiguration planning for a high dexterity modular self-reconfigurable robot for extra-terrestrial exploration

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HIGHLIGHTS

- Design of a homogeneous modular self-reconfigurable robot (ModRED) with 4-DOF.
- The connector mechanism design and advantages of a prismatic DOF are presented.
- Locomotion gaits are simulated (Webots) and implemented in the real ModRED system.
- The self-reconfiguration problem is modeled as a graph-based coalition formation.
- Experimental results find the best partition—reasonably low computational overhead.

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ABSTRACT

This paper presents a homogeneous modular robot system design based on four per-module degrees of freedom (DOF), including a prismatic DOF to increase the versatility of its reconfiguration and locomotion capabilities. The ModRED (*Modular Robot for Exploration and Discovery*) modules are developed with rotary-plate genderless single sided docking mechanisms (RoGenSiD) that allow chain-type configurations and lead towards hybrid-type configurations. Various locomotion gaits are simulated through the Webots robot simulator and implemented in the real ModRED system. This work also addresses the problem of dynamic reconfiguration in a modular self-reconfigurable robot (MSR). The self-reconfiguration problem is modeled as an instance of the graph-based coalition formation problem. We formulate the problem as a linear program that finds the "*best*" partition or coalition structure among a set of ModRED modules. The technique is verified experimentally for a variety of settings on an accurately simulated model of the ModRED robot within the Webots robot simulator. Our experimental results show that our technique can find the best partition with a reasonably low computational overhead.

1. Introduction

Modern space missions have an integrated mix of humans working with robots and autonomous systems on board spacecraft and in mission control. Nevertheless, in order to continue with exploration missions, it is necessary to keep developing and improving our space technologies. The benefits of new technologies will include extending exploration reach beyond human spaceflight limitations, reduced risks and cost in human spaceflight, enabling science, exploration and operation mission performance, increasing capabilities for robotic missions, use of robots and autonomy as a force multiplier, and autonomy and safety for surface landing and flying unmanned aerial vehicles (UAVs). One of the primary frontiers for exploration today involves planetary and lunar environments. Exploration in these environments can involve different robot tasks such as mobility and manipulation. Mobility tasks include surface, subsurface, aerial and in-space locomotion, from small machines to large systems that can carry materials, using modes of transport that include flying, walking, climbing, rolling, tunneling and thrusting. Manipulation tasks include force control, compliance, tactile control, dexterous manipulation, grasping, multi-arm control and tool use. Since payload is a critical concern, a lighter and more dexterous robot is preferable. Modular Self-reconfigurable Robots (MSRs) are systems that can execute multiple tasks when changing from one robot configuration to another without affecting the total payload [1,2].

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Modular robotic systems usually consist of an inventory of modules that may be assembled in different ways to form different robot configurations. This type of system is composed of a repertoire of multiple units with docking interfaces that may allow transfer of mechanical forces, moments, electrical power, and/or communication signals throughout the modules. The main philosophy behind these approaches is to divide a complicated system into functional modules with high portability, simplicity of maintenance, and logical clarity. Modular systems attempt to bring benefits such as versatility, robustness and low-cost fabrication over conventional fixed-parameter design. Their ability to rearrange their modules and to adapt to different circumstances allows them to cope with multiple tasks such as different types of locomotion and manipulation. One of the principal computational challenges in MSRs is to solve the self-reconfiguration problem, *i.e.,* how to adapt their shape autonomously so that they can change tasks or continue their operation after encountering obstacles or occlusions that impede their movement [3]. As a motivating example, we consider a scenario where a set of modules are deployed individually, possibly scattered on the ground within communication range of each other, from an airborne vehicle. The objective of these individual modules is to autonomously determine suitable multi-robot configurations, maneuver themselves to get within close proximity of each other, and finally, align and dock with each other to realize those configurations. In this paper, we focus primarily on techniques that enable the modules to determine their best configuration for performing their assigned task or operations; the maneuvering of the modules to get into their desired configurations is not the main focus of this paper and is considered as future work.

This paper focuses on presenting the development of a new homogeneous modular robot design, ModRED, and a novel self-reconfiguration technique based on modeling the problem as a coalition structure generation (CSG) problem in coalition game theory.[3] The main purposes of developing ModRED (*Modular Robot for Exploration and Discovery*) are to improve and implement techniques for automated exploration of initially unknown or little-known environments such as extra-terrestrial surfaces on the Moon or Mars or terrestrial regions with limited accessibility such as in urban search and rescue (USAR) scenarios. The self-reconfiguration approach focuses on the computational aspects of the problem faced by the individual modules to determine their "*best*" set of configurations that gives them an improved efficiency or value in performing their assigned task, while considering the costs in terms of energy expended to get in proximity of, and align and dock with each other to get into those configurations. The reconfiguration problem can be classified into two main phases, *i.e.,* planning or finding a suitable robot configuration, and the movement of modules to get into the selected configuration [4,5]. Our reconfiguration algorithm focuses on the first phase, *i.e.,* finding the best configuration to perform the robot's assigned task or operations in the current situation.

Section 2 summarizes the key contributions made in the modular robotics field so far. These developments have driven continuous improvement in aspects related to the mechanical design, as well as in the techniques used to provide solutions to the self-reconfiguration problem. Section 3 describes the ModRED system, with emphasis on its 4 degree-of-freedom (4-*DOF*) module design, communication architecture and electronics for navigation and sensing. In this work various locomotion gaits are simulated through Webots software and implemented in the real ModRED system to perform gait table-based locomotion tasks. In Section 4 the self-reconfiguration problem for modular robots is addressed, using a representation from coalition game theory called coalition structure graph (CSG). Coalition games are suitable for the MSR self-reconfiguration problem because the solution found by a coalition game ensures stability. Once the best partition or coalition of agents, corresponding to the best configuration of MSRs, has been found, the modules that have been determined to form the new configuration will remain together and will not try to leave the new configuration and attempt to combine with other modules. It is important to mention that in coalition game theory, the assimilation of agents into teams and the communication between agents is assumed to be free of cost. However, in MSRs there is a "cost" by expending energy to communicate with each other and physically move to each other's proximity to dock with each other. Also, solving the CSG problem that deals with finding the *best* or optimal coalition in a coalition structure graph is known to be an NP-hard problem with few existing heuristic solutions. To address these problems, in this paper we first develop a utility-based formulation for the costs corresponding to the dynamic reconfiguration problem in MSRs within a coalition game theoretic framework. Then we use a graph clustering algorithm to solve the CSG problem within this setting, using a polynomial time complexity and logarithmic approximation. To illustrate the operation of our MSR we have used the domain of robotic exploration of initially unknown environments. The experimental results using ModRED within the Webots simulator are shown in Section 5. The results show that the graph clustering technique can be successfully used to find the best configuration in the current scenario. Finally, concluding remarks about the advantages and limitations of both the ModRED system and the self-reconfiguration technique are presented in Section 6.

2. Related work

The field of modular robotics has advanced from proof-of-concept systems to elaborate simulations and physical implementations. Since the first modular robotic system development, the size, robustness and performance have been continuously improving [6–11]. In 1988, T. Fukuda introduced the concept of a reconfigurable robotic system with the biologically inspired cellular robot (CEBOT) [12,13]. Each module had independent processors and motors, and could communicate with each other to approach, connect and separate automatically. The idea was popularized by the work of M. Yim at Standford University in the early 1990s, whose work extended the idea to fully autonomous robots including locomotion [14,15]. Later on, G. Chirikjian, S. Murata and E. Yoshida developed lattice-style configuration systems [16–19]. In the later 1990s K. Kotay, D. Rus and A. Castano also developed hardware, but their larger contributions came in the distributed programming aspects [20–22]. This included seminal trends in developing provable distributed algorithms and decentralized control based on local communication by W.M. Shen [23]. Two of the areas of research include configuration, self-recognition and kinematic planning of the motions for rearrangement between configurations [24]. Up to now, it is possible to find different modular robot designs. Each design has mainly focused on certain aspects such as flexible form factor, utilizing different degrees of freedom, high torque-to-weight ratio, ease of docking/undocking and power management [25–35].

In the applications of MSR systems such as planetary exploration and earthquake rescue missions where each module has to be highly autonomous for its effective maneuvering, higher per-module dexterity is required. In a previous study [36] we discussed the number of available DOF per module in current and past MSR systems. For instance, Polybot, CKbot and Molecube with 1 DOF, and CONRO, Polypod, MTRAN III with 2 DOF presented the advantages of a lower number of DOF to simplify the function of a single module. However, a relatively large number of modules is needed

[3] Videos of the project can be found at http://cmantic.unomaha.edu/projects/modred/index.htm.