ModRED: A Modular Self-Reconfigurable Robot For Autonomous Extra-terrestrial Exploration and Discovery

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I. Introduction

Navigating autonomous robots through unpredicatable, hazardous and occluded terrains is a crucial operation in extra-terrestrial exploration. In the ModRED (**Mod**ular Self-Reconfigurable **R**obot for **E**xploration and **D**iscovery) project we are developing a modular self-configurable robot (MSR) that is capable of navigating in rough terrains such as those found in many extra-terrestrial environments. In this paper, we report the development of a prototype version of the ModRED MSR and preliminary simulations of the robot to follow a simple inchworm-like crawling pattern. The final objective of the project is to develop distributed coordination algorithms for the different modules of the ModRED. These coordination algorithms would enable the ModRED to dynamically and autonomously make decisions to adapt its configuration based on its current configuration and motion capabilities.

II. ModRED Module Construction

A single module of the ModRED is essentially a 4-link serial kinematic chain. It is composed of an end bracket to which another module can connect, a first half-body containing actuators and drivetrain components, a second half-body also containing actuators and drivetrain components, and another end bracket for module docking. The two end brackets are connected to the respective half-bodies by revolute joints, and the central axis running the length of the two half-bodies is the common location of 1 prismatic joint and 1 revolute joint, giving the MSR module 4 DOF overall. The two end brackets can rotate $\pm$ 90 degrees, and the rotation along the central axis of the module is unbounded. This 4-DOF architecture provides a more versatile set of motion possibilities than many other chain-type MSR designs. One of the novel features of the robot is the use of 2 DC micromotors to drive the 4 motion axes. This is achieved through a special clutch mechanism actuated by binary (solenoid) actuators. In this way, a single motor may drive either 1 or 2 DOF at a time, in either a consistent or opposite direction. The clutch mechanism in each half-body includes three friction interfaces for changing between drive states. The main drive shaft is connected to the motor through a set of right-angle bevel gears. Two solenoids are used to engage or disengage the motion axes through the aforementioned friction interfaces. A third solenoid also provides change of direction to one DOF relative to the other by engaging either a chain coupling or a geared coupling to its output shaft. The end bracket rotations are achieved by engaging the relevant clutch and providing power through the main drive shaft and a set of miter gears. To activate the translational DOF, either the chain drive or geared coupling (dependent on desired direction) is engaged, thus rotating a ball screw to translate the module half-bodies relative to each other, either expanding or contracting the space between the half-bodies. Throughout the translational movement, a pair of linear guides support and align the half-bodies. The rotation about the module's long axis is achieved very similarly to the prismatic DOF, except that rather than convert the rotational input to translation using a ball screw, the input rotation is directly used to drive the DOF. The purpose of using 2 motors in conjunction with several small solenoids to drive 4 DOF was based on the desire for weight reduction. In fact, in the current prototype construction, the weight of each motor is roughly 100 g, and the added drivetrain components involved in the clutching mechanisms weigh approximately the same. Refinement of the design could easily produce a net weight reduction using this novel drive train configuration. A CAD rendering of the module is shown in Figure 1(left).

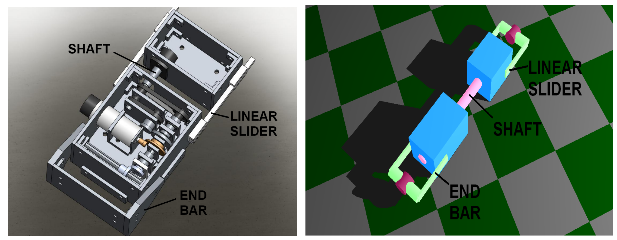

Fig. 1. A single module of the ModRED: the CAD rendering of the module(left) and the simulated module in Webots (right).

III. ModRED Gait Simulation

We have simulated the MSR robot using the Webots simulation platform. Webots is a powerful multi-robot simulation platform that provides accurate modeling of robot features and the ability to simulate the physics of the environment. Simulation of the ModRED robot is essential to fully under-

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stand and refine its kinematics. We can accurately control forces with which each part's action is effected so that the desired motion is obtained. This is very important while designing the robot's motion because inaccurate forces can cause a module and the entire robot to lose stability while moving and fall down. Secondly, testing invidvidual modules' movements allows us to verify how those movements manifest in the overall robot's motion. The software model of the robot was based on the CAD diagrams of ModRED described in Section II. A figure of the ModRED module simulated within Webots is shown in Figure 1(right). Figure 2 shows snapshots of the successive phases in the robot's inchworm-like motion.

IV. Dynamic Module Reconfiguration

The primary action of ModRED is to navigate itself within its environment. Navigation is manifested by different gait patterns of the robot. Currently, gait patterns are "hand-crafted" - they are first determined off-line by analyzing the movements of individual parts and determining the correct sequence that results in the desired gait pattern. These individual movements are then programmed on the robot. A feedback-based controller could also be programmed on each module that prescribes a certain gait pattern in response to the robot's navigational performance. However, there are certain drawbacks of this approach - it would not scale gracefully with the number of modules. Also, an exhaustive enumeration of gait patterns would be infeasible to build and perhaps include motions that are unnecessary for normal maneuver.

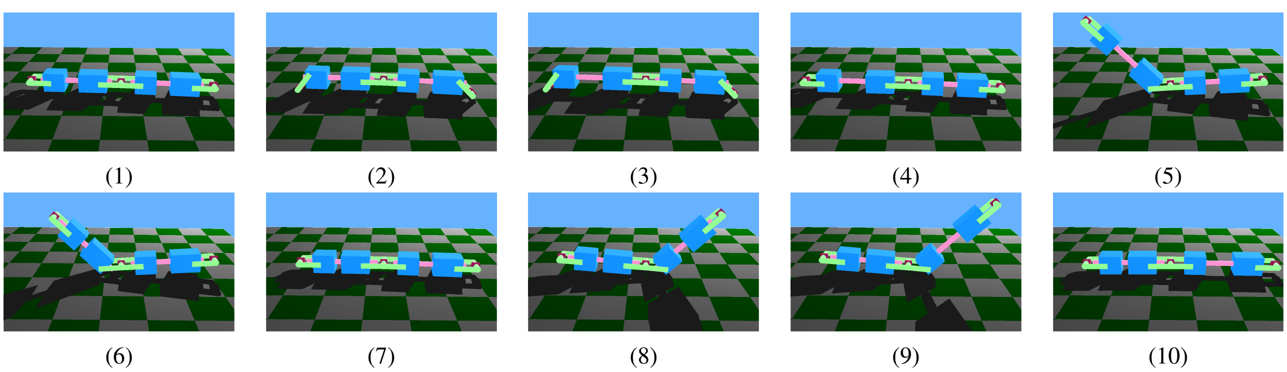

Fig. 2. Successive movements of the different parts of two modules of the ModRED that produces an inchworm-like motion: (1): initial flat configuration, (2): raise end bars, (3) expand shaft of rear module, (4) lower end bars, (5) raise rear module, (6) contract shaft of rear module, (7) lower rear module, (8) raise front module, (9) expand front module, (10) lower front module to regain flat configuration.

To address these challenges, we plan to investigate a dynamic mechanism that coordinates the different modules of the robot autonomously to reconfigure it. Previous research on coordinating the modules of a MSR is mainly focussed on control mechanisms[1]. The coordination problem between different modules of an MSR is a cooperative one where modules are incentivized to operate in tandem with other modules to effect the robot's navigation. We posit that coalitional game theory, a branch of microeconomics emphasized in multi-agent systems, provides a suitable model for the cooperative coordination problem in a MSR. To enable automated decision-making by the ModRED's modules to coordinate their actions with each other two fundamental questions need to be addressed: (1) What is the best module or set of modules to pair with? (2) What is best set of connections to have with the neighboring modules? Within the framework of a coalition game these issues can be addressed by assigning appropriate utility values to the different actions or movements available to a module and have the modules collectively select the set of movements that maximize their individual utilities as well as the utility of the entire robot. Some crucial questions need to be answered while designing such a framework, which includes representational and computational issues. Currently, coalition games can be represented in various formats including voting games, graphical games, networked representations and logical constraints. Our objective would be to select and adapt a representation that is amenable to the MSR coordination problem. Additionally, the most important criteria for the navigation of an MSR is its stability. We have to carefully investigate how the stability criterion of the MSR and its modules maps to the convergence or equilibirum criterion of the coalition game Finally, determining the utility values for the individual agents (modules) comprising the MSR is essential in finding a solution to the coalition game.

We plan to discuss our experience in building multi-robot teams using coalition formation techniques [2], [3] to answer some of these questions.

References

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