Toward Unicorns

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***Abstract*—We present a fully autonomous modular robot system that can perform complex reactive high-level tasks (requiring reconfiguration) in an unknown environment without external sensing or control. TODO: Describe system capabilities in detail here.**

I. Introduction

Modular self-reconfigurable robot (MSRR) systems are composed of a number of simple repeated robot elements (called *modules*) that connect together to form larger robotic structures. These systems can *self-reconfigure*, changing their shape (*i.e.* the connective structure of the modules) to meet the needs of the task at hand. In principal, these systems can address a wide variety of tasks by transforming into a wide variety of morphologies. The traditional approach to achieving flexible robots is to build monolithic systems that are highly capable, but also highly complex (*e.g.* large humanoids). Self-reconfigurability is an elegant, scalable alternative: since the shape of the robot is not fixed, each individual task can be solved with a morphology that is only as complicated as it needs to be.

Over the past three decades, dozens of modular robot systems have been built **TODO: cite** . Existing literature provides ample evidence of the ability of MSRR hardware to reconfigure, algorithms for reconfiguration planning with hundreds of modules, a number of interesting morphologies suited to object manipulation and locomotion over varying terrain, methods and interfaces for programming, controlling, and simulating modular robots, and recently, systems that select appropriate configurations and behaviors for an MSRR automatically given a high-level specification of a task **TODO: cite** .

These capabilities are impressive, and each represents a significant research accomplishment in its own right. However, in order to truly live up to their promise of flexible capability in the real world, MSRR systems must demonstrate autonomy: moving, navigating, interacting with objects, and self-reconfiguring, all in unknown environments and without external localization or control. To our knowledge, this paper represents the first example of a truly autonomous MSRR system accomplishing tasks in an unknown environment.

Traditional robotics literature provides numerous examples of robots operating autonomously in unknown environments **TODO: cite** . Our system goes beyond this existing work because it has the unique ability to recognize and act on situations in which reconfiguration is needed to complete a task. Through hardware experiments, we demonstrate that autonomous self-reconfiguration allows our system to complete tasks that would have otherwise been impossible.

The remainder of the paper is structured as follows. **TODO: complete paper structure paragraph**

II. Related Work

A. Mapping and Navigation

TODO: Jonathan, can you add some relevant literature here?

B. Modular Robots Completing Tasks

There are many examples of MSRR systems accomplishing low-level tasks such as object manipulation **TODO: cite** and various modes of locomotion [10]. Recently work includes a system which integrate many low-level capabilities of a MSRR system in a design library, and accomplishes high-level user-specified tasks by synthesizing elements of the library into a reactive state-machine [4]. While this system demonstrates autonomy with respect to task-related decision making, it is designed to operate in a fully known environment with external sensing.

Modular robots have long been regarded as having the potential to make impact in unknown environments (such as search and rescue scenarios), because self-reconfiguration theoretically gives them the flexibility to respond to whatever they encounter [11, 12]. However, examples of MSRR actually operating in unknown environments are very limited. To our knowledge, no modular reconfigurable robot system has been used for SLAM. We think our system has more autonomy in an unknown environment than any existing modular robot system, and represents an important step toward the application of MSRR in the real world.

There is work on mapping with swarm robot systems. The Millibots system has demonstrated the ability to map a partially unknown environment when operating as a swarm [3]. The autonomy of the Millibot swarm is limited: a human operator makes all high-level decisions, and is responsible for navigation using a GUI. Certain members of the swarm are designated as "beacons," and have known locations, making the environment only partially unknown.

The swarm-bots are a MSRR system that has been applied in exploration [1] and collective manipulation [5] scenarios. Like the Millibots, exploration is demonstrated in partially unknown environments, with some members of the swarm acting as "beacons" with known location. In a collective manipulation task, the swarm-bots have limited autonomy, with a human operator specifying the location of the manipulation target and the global sequence of manipulation actions. The swarmanoid project (successor to the swarm-bots), moves a step beyond this capability, using a heterogeneous swarm of ground and flying robots (called "hand-", "foot-", and "eye-" bots) to perform exploration and object retrieval tasks in unknown environments [2].

C. Autonomous Self-Reconfiguration

Autonomous reconfiguration has been demonstrated with several modular robot systems. CKbot, Conro, and MTRAN have all demonstrated the ability to join disconnected clusters of modules together [13, 8, 6]. In order to align, Conro uses infra-red sensors on the docking faces of the modules, while CKBot and MTRAN use a separate sensor module on each cluster. In all cases, individual clusters locate and servo towards each other until they are close enough to dock.

While these proof-of-concept experiments demonstrate the ability to reconfigure, they could not be directly used as part of a larger system to complete tasks. These experiments do not include any planning or sequencing of multiple reconfiguration actions in order to create a goal structure appropriate for a task. Additionally, because these are all chain-type modular robots, individual modules are not able to locomote on their own, and mobile clusters of modules are limited to slow crawling gaits. Consequently, reconfiguration is very time consuming, with a single connection requiring 5-15 minutes.

Other work has focused on reconfiguration planning, but not autonomous reconfiguration. Paulos et al. present a system in which self-reconfigurable modular boats self-assemble into functional floating structures, such as a bridge [7]. Like the SMORES-EP modules used in this paper, individual boat modules are able to move about the pool, allowing for rapid reconfiguration. However, external localization is provided by an overhead AprilTag system.

To our knowledge, there are no examples of a MSRR autonomously making the decision to reconfigure in response to sensed environmental conditions and then actually taking that action in order to complete a task. In [2], hand-bot and foot-bot elements of the swarmanoid system connect and disconnect in order to complete a book-retrieval task. However, the decision to take this action is not made autonomously by the robot in response to sensed environment conditions.

III. Hardware

A. SMORES-EP Modular Robot

Our system is built around the SMORES-EP robot, but could easily be adapted to work with other hardware platforms. In this section, we provide a brief introduction to the technical capabilities of SMORES-EP.

Each module is about the size of an *80mm cube*, and has four actuated DoF - three continuously rotating faces (left, right, and pan) and one central hinge (tilt) with a 180° range of motion (Fig. 1). The DoF marked left, right, and tilt have axes of rotation that are parallel and coincident. A single module can use its left and right wheels to drive around as a two-wheel differential drive robot. All four faces of the SMORES-EP module have electro-permanent (EP) magnets that serve as a high-strength, low-energy connector for self-reconfiguration [9]. Any face of one module can connect to any face of another.

The magnetic connectors can also attach to objects made of ferromagnetic materials (such as steel). By taking advantage of this capability, SMORES-EP modules can use their magnets to attract, lift, and carry metal objects. Provided the attachment surface is flat and smooth, the attachment force between a SMORES-EP face and a strongly ferromagnetic object can be as high as 90N [9].

Some of the motions a SMORES-EP cluster can perform are limited by the strength of the magnetic connectors, which can support the weight of at most three modules cantilevered horizontally against gravity. This limitation is alleviated in some cases by using rigid connector plates, which are screwed into the faces of two modules to create a strong permanent connection between them. Using connector plates, up to four modules can be cantilevered before exceeding the torque limits of the motors. However, because the connector plates must be manually screwed into place, modules with connector plates cannot self-reconfigure.

Each module has an onboard battery, microcontroller, and 802.11b wireless module to send and receive UDP packets. In this work, clusters of SMORES modules were controlled by a central computer running a Python program that sends wireless commands to control the four DoF and magnets of each module. Battery life is about one hour (depending on motor, magnet, and radio usage), and commands to a single module can be received at a rate of about 20hz. Wireless networking was provided by a standard off-the-shelf router, with a range of about 100 feet.

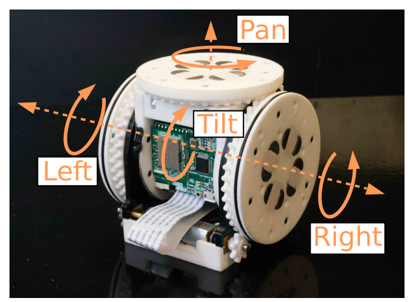

Fig. 1. SMORES-EP module

B. Sensor Module

In most MSRR systems, individual modules have very limited sensing capability, so autonomous reconfiguration is accomplished by including a sensor or camera module as a component of each cluster of modules in the system. In our system, the sensor module is capable not only of determining the position of individual modules relative to the cluster, but also includes an RGB-D camera that facilitates SLAM in an unknown environment.

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