Engineering Self-Adaptive Modular Robotics: A Bio-Inspired Approach

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Abstract— **In nature, animal groups achieve robustness and scalability with each individual executes a simple and adaptive strategy. Inspired by this phenomenon, we propose a decentralized control framework for modular robots to achieve coordinated and self-adaptive tasks with each modules performs simple distributed sensing and actuation [1]. In this demonstration, we show that such a framework allows several different modular robotic systems to achieve self-adaptation tasks scalably and robustly, examples tasks include module-formed table and bridge that adapt to constantly-perturbed environment, a 3D relief display that renders sophisticated objects, and a tetrahedral robot that performs adaptive locomotion.**

I. INTRODUCTION

Biological systems gain a tremendous advantage by using vast numbers of simple and independent agents to collectively achieve group behaviors, e.g. fish schooling. In such systems, each local agent executes a simple adaptive strategy while the system as a whole archives coordinated behavior and is highly adaptive to local changes. In addition, such a strategy is scalable to the number of agents. This biological self-organizing principle has inspired our recent control framework in programming modular robots [1].

In this paper, we demonstrate several modular robotic systems and tasks that can be formulated within our control framework, including forming self-adaptive structure, performing adaptive grasping, and achieving adaptive locomotion. Although these robotic systems and tasks are fundamentally different, our control framework is able to capture all of them and allow them to achieve the desired self-adaptive tasks. In addition, it is scalable to the number of modules and robust towards real-world sensing and actuation. In [2], we explore the theoretical properties of such control strategy and analytically show that this class of algorithms exhibit superior performance in self-adaptive tasks. This demonstration is also a composition of various self-adaptive modular robotic tasks that coincides with our previous theoretical results.

Our algorithmic framework is simple and fully decentralized. Each modules in the system is viewed as an independent and autonomous agent. Modules achieve the desired global tasks through inter-module cooperation. In addition, the system can autonomously adapt to changing environments, even though each module executes only a very simple control law. Recently, we also show that such control strategy is closely related to a class of multiagent algorithms called distributed consensus [1], [2]. Here, we demonstrate several tasks on two different types of modular robot systems. In the first type of modular robots, each module is equipped with a rotary actuation and tilt sensor. We show how our control framework allow such robotic system to achieve environmentally-adaptive structure formation, e.g. forming a self-adaptive table. In the second type of modular robots, each module is composed of a linear actuator and pressure sensor. We show that a tetrahedral robot formed by such modules is capable of performing locomotion that adapts to different terrain conditions.

II. APPROACH

We first describe the design of our modular robot, and we then present a brief overview of the algorithmic framework[1].

A. Module Model

Here, we describe the modular robot model and the capabilities associated with each module. We view each module as an *independent and autonomous unit* that has the following capabilities:

Computation: All modules executes identical control law. We assume that the computational power of a single module is limited, and our focus is on simple local rules that do not require complex calculations.

Communication: Each module can communicate with its immediate physically-connected neighbors.

Actuation: Each module is equipped with an actuator. This can be either a rotary or a linear actuator. For example, we equip each module with a rotary motor for the modular gripper applications, while we provide linear actuators for the terrain-adaptive bridge and tetrahedral robot.

Sensing: Each module is equipped with a sensors suited to different robotics applications. In the self-balancing table and terrain-adaptive bridge, a tilt sensor is incorporated into each module. In the modular gripper and pressure-adaptive column, a pressure sensor is associated with each module.

Task: Each task is described in terms of inter-agent state constraints. For example, in the self-balancing table application, we specify that each agent needs to maintain zero-tilt angles with all of its neighbors. In the case of the modular gripper, we specify that each module must achieve an equal pressure state with all of its neighbors.

B. Algorithm

In this section, we provide a brief overview of our approach. Our framework is based on an iterative sensing and

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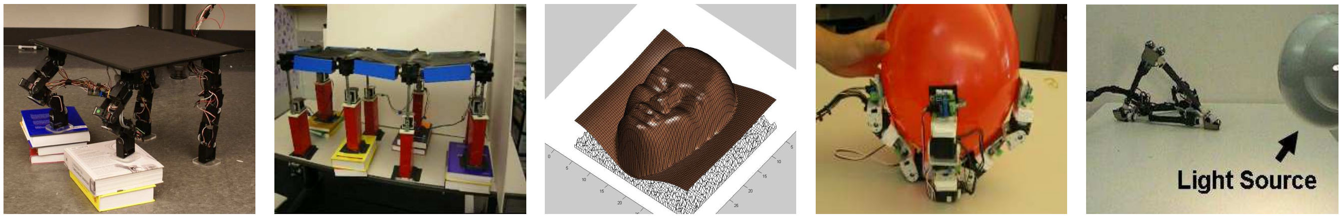
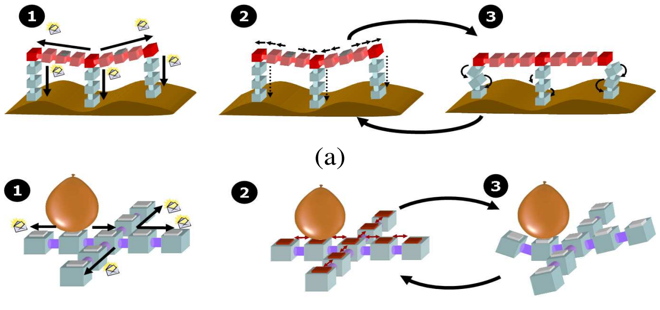
[1] For further details of hardware design and algorithm, please see [1]



(a) (b) (c) (d) (e)

Fig. 1. Different self-adaptation Tasks (a) Self-balancing table. The module-formed legs are capable of maintaining table surface level irrespective of tilt changes (b) Terrain-adaptive bridge. The bridge is able to achieve a flat bridge surface when it is placed on a rough terrain. (c) A 3D Relief display that is capable of rendering complicated shapes. (d) A modular gripper. The modules can cooperatively form a configuration that grasps a fragile object, e.g., a balloon. (e) A modular tetrahedral robot performs locomotion by a sequence of self-adaptations to the external environment.



(a)

(b)

Fig. 2. Algorithmic overview of the self-adaptation tasks. Step 1: Modules start passing messages to their neighbors to identify their local connectivity. Step 2 and 3: Modules perform iterative sensing and actuation until they converge to the desired state

actuation procedure: once a desired task has been specified, all modules sense the environment and coordinate to perform actuation until the desired goal has been reached. Here, we use a self-balancing table and a modular gripper as examples to illustrate our proposed algorithm (as shown in Fig 2). Our algorithm can be divided into the following three steps:

Step 1 (Initialization): Modules start sending messages to their neighbors. In the modular gripper case, this process is initiated as soon as one of the modules starts sensing the presence of an object. Modules transmit these messages to identify their neighbors and to map local connectivity.

Step 2 (Sensing): At each time step, those modules that are equipped with sensors start propagating their sensor readings to neighboring modules. In the self-balancing table, these messages contain sensory information and are aggregated by pivot modules (dark red modules). After collecting all the messages, the pivot modules then transmit the aggregated information to supporting modules (blue modules in Fig 2 (a)). In the case of the modular gripper, each module simply transmits its current pressure readings to its immediate neighbors.

Step 3 (Actuation): After receiving the sensory information, each modules controller uses that data as input from which to compute appropriate actuation parameters. In [2], we propose a generalized distributed consensus approach to derive our control law. The generalized form of the control law is: $x_i(t+1) = x_i(t) + \alpha \cdot \sum_{a_j \in N_i} g(\theta_i, \theta_j)$, where $x_i(t)$ represents state of module i at time t and $g(\theta_i, \theta_j)$ is a feedback that module i receives from neighboring module j. We showed that as long as g is appropriately designed, our modules will eventually achieve the desired state [1]. Empirically, this approach shows robustness against real world sensing and actuation noise.

III. ROBOT DEMONSTRATIONS

In this video demonstration, we show five different experimental results from robots operating under our framework.

Self-Balancing Table/Bridge: The robot is composed of four supporting groups (legs), and each composed of three modules.The surface group modules are replaced by a single rigid surface and has the tilt sensor mounted in the middle. We place the self-balancing table on several terrains of varying roughness and tilt angle. Our results showed that the robot is capable of maintaining a level table surface irrespective of initial conditions and subsequent perturbations (Fig 1 (a)(b)).

Self-Adaptive Structure Simulations: We also construct several self-adaptive structure simulations to examine scalability of our algorithm, including an adaptive bridge, a 3D building, and a 3D relief structure. Our result show that this approach is scalable to the number of modules (Fig 1 (c)).

Adaptive Grasping: We further demonstrate how a module-formed gripper achieves adaptive grasping via "pressure consensus" formation among modules. We gave the robot an inflated balloon to carry. The gripper was capable of grasping the balloon with uniform pressure. In addition, the robot autonomous adjusts to maintain a uniform pressure state when the it is perturbed by exogenous force (Fig 1 (d)).

Adaptive Locomotion: Finally, we demonstrate that this approach can be applied to a module-formed tetrahedral robot's adaptive locomotion tasks. In our experiment, the robot successfully moved toward the light source at a speed of 10cm/sec on a flat terrain. When the environmental condition allows agents to exploit gravity to assist locomotion, e.g. on a steeper slope, the locomotion cycle time will adapt to become shorter (Fig 1 (e)).

REFERENCES

[1] C.-H. Yu and R. Nagpal, "Self-adapting modular robotics: A generalized distributed consensus framework," in *Proc. of ICRA*, 2009.

[2] ——, "Sensing-based shape formation tasks on modular multi-robot systems: A theoretical study," in *Proc. of AAMAS*, 2008.