Sensors and Actuators A 173 (2012) 267–276

Contents lists available at SciVerse ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

Design of a miniature switchable connection system for stochastic modular robots

Guoqiang Fu[a,b,*], Arianna Menciassi[a], Paolo Dario[a]

[a] The BioRobotics Institute, Scuola Superiore Sant'Anna, Pisa 56025, Italy
[b] Center for Intelligent and Biomimetic Systems, Shenzhen Institutes of Advanced Technology, Chinese Academy of Sciences, Shenzhen 518055, China

ARTICLE INFO

Article history:
Received 8 June 2011
Received in revised form
29 September 2011
Accepted 30 September 2011
Available online 12 October 2011

Keywords:
Magnetic interaction
Modular robots
Shape memory alloy actuator
Stochastic self-assembly
Switchable connection system

ABSTRACT

This paper presents the design and implementation of a MIniature SwitchAble (MISA) connection system for stochastic modular robots. The MISA connector consists of attaching, aligning, locking, detaching and holding mechanisms. The connection function can be switched on and off by controlling shape memory alloy (SMA) actuators. Furthermore, it possess functions of self-attachment and self-alignment through magnetic interaction under random collision condition. The design details and prototype construction are presented. The preliminary experiments and results demonstrate feasibility and performance of this miniature connector. The potential application is to integrate it into modular microrobots.

1. Introduction

In recent years, many modular robots for self-assembly, self-reconfiguration, and self-repairing have been developed because these systems possess the potential advantage of versatility through reusability of modules, low cost through mass fabrication of modules, fault tolerance, and ease of repair by replacing not functioning modules [1,2].

A further challenge in modular robotics is the scalability of systems. Implementations of the self-assembling or self-reconfigurable systems with hundreds of modules are hampered by limitations and uncertainties encountered in the physical world [3]. The used modules could be active modules that are self-propelled by on-board actuator and energy, also could be passive modules that are externally propelled by external environmental energy because they do not have onboard locomotion unit. In comparison with active modules, the passive modules have advantage of decreasing complexity and size of each module because some onboard components for propelling module are not required, resulting in increasing the number of modules. In stochastic modular robotic systems, passive modules are bonded together through a random motion, and there is no need on path planning in this kind of quasi-deterministic assembly process, as well as no computation or actuation is required from modules before they connect with each other.

Because passive modules move stochastically, so it is impossible to control the motion of single passive module precisely same as that for self-propelled modules, thus the results of self-assembly could be random or programmable depending on the function of connection system of modules. If connection system is not switchable, thus passive modules will connect to each other randomly and the final assembled results are not predicable. The programmable self-assembly of stochastic modules could be realized by controlling the order of switching on and off connection systems [4], so it is critical to develop a switchable connection system for stochastic modular robots.

This paper is organized as follows. Section 2 outlines requirements on docking system for stochastic modular robots and summaries related work. Secion 3 presents the design details of MISA connection system by explaining attaching, detaching, locking and holding mechanisms. The fabrication of prototype is presented in Secion 4. Section 5 establishes theoretical model of magnetic field of magnetic arrays, theoretical model of forces produced by two-way shape memory alloy (SMA) actuator, and theoretical model of force on elastic beam, respectively. Then the feasibility of programmable self-assembly using MISA connection system is analyzed in Section 6. Section 7 presents experimental

* Corresponding author at: Center for Intelligent and Biomimetic Systems, Shenzhen Institutes of Advanced Technology, Chinese Academy of Sciences, Shenzhen 518055, China.
E-mail addresses: furobot@hotmail.com (G. Fu), arianna@sssup.it (A. Menciassi), dario@sssup.it (P. Dario).

0924-4247/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.sna.2011.09.036

setup and results on docking and undocking performance of connection system. Finally, this paper is ended with conclusions and prospectives on future work in Secion 8.

2. Design requirements and related work

The docking process between two stochastic modular robots is different from that between two autonomous modular robots. During docking process between two autonomous modular robots, aligning sensors are needed to guide robots to docking target; moreover, the localization of robots is known before two robots approach to each other. The situation is quite different when two stochastic modular robots dock to each other, firstly, they move randomly and the docking action only takes place when they collide with each other by chance. The random collision is uncontrollable, in order to achieve self-assembly/disassembly of stochastic modular robots, the connection/docking system should possess following capabilities:

1. *Attractive force*: the attractive force between two docking systems should be strong enough to attract them together once they move close to each other by chance.
2. *Binding force*: after attaching with each other, the bonding force should be strong enough to resist the external disturbing force in order to keep stable connection.
3. *Reversible*: the bond can be re-established after it was broken by detaching force.

Even though with abovementioned capabilities, the assembled results are still not predicable because of random connection. In order to achieve programmable self-assembly of stochastic modules, one additional capability named *switchable* is proposed for connection system. The connection system can adjust attractive force and bonding force according to need with the *switchable* capability. For example, after a connection system decreases its attractive force, it will not be able to catch other connection systems, or be caught by other connection systems. The different phases of docking action are defined as "switched on" and "switched off". By controlling the order of "*switched on*" and "*switched off*" of docking system, the assembled results will be programmed. In addition, acceptable overall size of connection system and constraints originating from applications should also be considered during design.

Several kinds of stochastic modular robots at centimeter scale with different switchable connection systems have been developed till now. In some developed systems [3–5], the floating modules in a chamber that is filled with liquid are binded using near field forces produced by fluidic flow with thermorheological valving, but these systems need very complex apparatus and continuous power supply. Some connection systems [7–9] are based on use of electromagnets, these docking methods are not power efficient because they need to be supplied with continuous power before and after connection. Swiveling permanent magnets [6,10] and Magswitch [11] are power efficient, but they are actuated by electric motors, thus their overall sizes are quite large as a result they are not suitable for modules at millimeter scale. Furthermore they are not self-aligning, thus they can't guarantee electrical connection. They are also lack of locking mechanisms that is used for sustaining rigid connection. The connection system consisting of switchable electro-permanent magnets as described in [12] is small, however, it needs high current to achieve switch function, and it is lack of locking mechanisms for reliable connection. To achieve programmable self-assembly of stochastic modular robots at millimeter scale, development of a miniature switchable connection system with characteristics of low power consumption and reliable connection represents an emergent need and a challenging task.

3. Design of connection system

The MISA connection system for stochastic modular robots includes locking device, detaching device and holding device besides array of magnets on mating face used for attachment and alignment. The overall view of mechanical design is illustrated in Fig. 1.

As mentioned above, the size of connection system should be as small as possible in terms of miniaturization. Currently it seems that it is recommendable to use a commercial electric motor for actuating this docking system because of space constraint. The smallest off-the-shelf electric motor that we can find with authors' best knowledge is still larger than 2 mm × 8 mm with very low torque, considering the need of transmission system, the overall size of motor actuation system becomes larger.

The high force, large stroke, low voltage, the favourable effects of miniaturization and simple construction of SMA driven devices are the major reasons why SMA actuators are chosen for small scale actuation systems [13–18]. The MISA connection system uses SMA springs as actuators. The first application is that SMA springs work as linear actuators for detaching two connected docking disks away from each other. The second application is to constitute a differential actuation system with two SMA springs for locking and unlocking. The third application is to use SMA springs to bend an elastic beam with hook on its tip for holding docking disk in retracted state or releasing docking disk from retracted state.

3.1. Attaching and aligning mechanisms

In order to attach stochastic module from surrounding environment, attracting force must be presented between two docking systems. Magnetic force, capillary force, electrostatic force and fluidic force can induce attracting behavior. By making comparison among these forces, magnetic force has the advantages of natural interaction, ease control and no power consumption, so it is chosen as attracting force between two docking system. With the precise arrangement of permanent magnets on docking disk, it is also possible to achieve *self-aligning* under random motion situation because modules will be automatically rotated by magnetic torque when they get closely. In order to eliminate misalignment induced by magnetic attractive force, the docking disk is designed with special shape, namely 4-way symmetric pins and holes are placed on

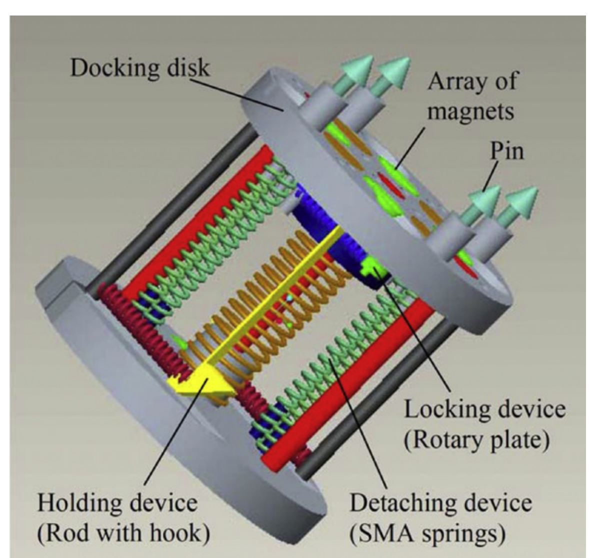

Fig. 1. Overall view of mechanical design of docking unit.