Docking Process Analysis in Self-repairing Robots

Yanqiong Fei, Pengwei Gong, and Libo Song
Research Institute of Robotics, Shanghai Jiaotong University
Email: fyq@sjtu.edu.cn

***Abstract*—For the self-reconfigurable robot, one of its main functions is its self-repairing ability. First, the mechanical structure of the self-repairing robot is presented, which composes of a central cube and six rotary arms. In order to finish the self-repairing action, the disconnection/connection mechanism of each module is designed, which consists of one expansile hole (connection hole) and one extension peg (connection peg). Then, the docking process is analyzed with the geometric method. Contact states in the docking process are explained in detail. At last, a simulation of six-module is shown that the modules can finish the docking process effectively.**

***Index Terms*—self-reconfigurable robot, self-repairing, process, module**

I. Introduction

Self-reconfigurable modular robot (SMR) consists of standardized electromechanical modules which can dynamically change their geometric structure to complete different requirements of various tasks and environment. They can be classified as the chain-type, the lattice-type and the hybrid [1]. Chain-type self-reconfigurable robots, such as ModRED [2], Moteins [3] have a higher degree of mobility than lattice-type systems do. They are able to reach any point in the space. Lattice-type robots, on the other hand, can easily self-reconfigure and are suitable for forming various static configurations, but they have difficulty in generating motion, such as a cubic structure (3-D self-reconfigurable mechanical system) [4], Fracta 3D [5], two hemispheres joined modules (ATRON) [6], the crystal module (Crystalline) [7], Miche [8] and M-Cube[9], [10]. Hybrid architecture takes advantages of both previous architectures. Roombots [11] and SMORES [12] are hybrid type self-reconfigurable systems. SMRs are potentially more versatile, flexible, and capable than fixed-architecture robots. The reconfigurable ability allows a robot or a group of robots to disassemble and reassemble machines to form new morphologies that are better suitable for new tasks or environments.

For SMRs, one of the most important features is its self-repairing function, which makes it more robust and reliable. If some modules of a system fail, the system can eject faulty modules and replace them with spare modules to keep the completeness of the system configuration. This characteristic is unique compared with the fixed-architecture system. However, it's common in biological systems.

In this paper, the configuration of a homogeneous and lattice SMR is described. Its mechanical structure and disconnection/connection mechanism are designed. Based on different contact states, the docking process is analyzed with the geometric constraint method.

II. Mechanical Design

A. Structure of Module

The self-reconfigurable robot "M-Cubes" is proposed (Fig.1). In M-Cubes, the output of the DC motor is delivered to six transmission shafts (located in the centers of the cube) using five bevel gears. It uses the peg-in-hole principle to finish the docking process. In M-Cubes, each module in M-Cubes composes of a central cube and six rotary arms which are distributed on the six sides of the central cube. The size of the central cube is 23 cm. Each rotary arm can rotate 90°×n about the axis of the cube (n=1, 2, 3, …). The rotary arm has a connection peg and a connection hole. The connection peg has a locking system, which can lock the connection with three beads when the connection peg inserts into other module's connection hole. Then, two modules can connect to each other firmly. The connection arms can rotate along their axes. With the connection/ disconnection mechanism, M-Cubes can discard the faulty module to finish the self-repairing action.

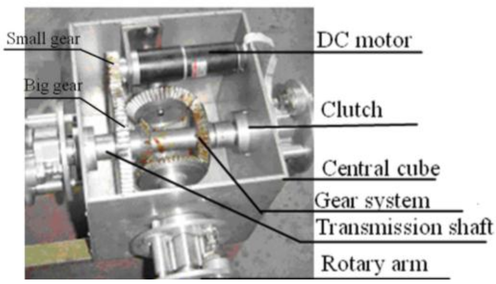

Figure 1. Inner mechanics of M-Cubes module.

Fig. 1 shows the inner mechanics of the M-Cubes module. There's a Maxon DC motor in the central cube, which is the power supply of the connection arms. The rotation of the motor is transmitted to the six output axes by two-gear reducer and five cone-shaped gears.

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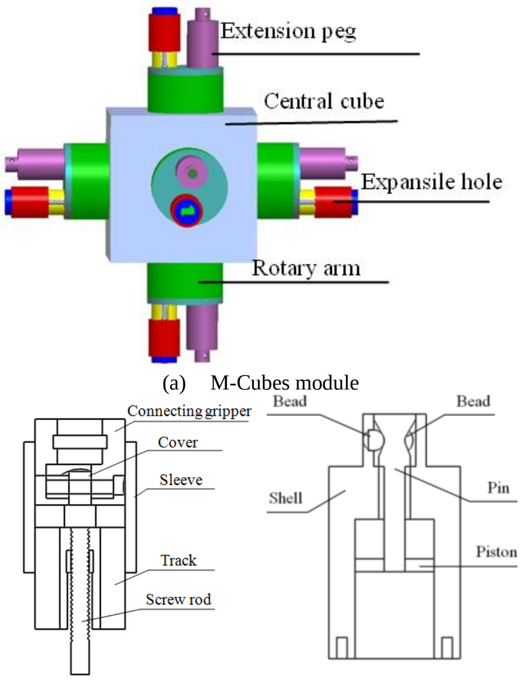
B. Disconnection/Connection Mechanism

Each rotary arm (Fig. 2 a) can connect with/disconnect from other modules. If a module is damaged, its neighbors should be able to disconnect it from the system without any constraints from the faulty module. For these purposes, we design the disconnection/connection mechanism that allows disconnection to be accomplished at either side of the connection.

Each rotary arm consists of one expansile hole (connection hole) and one extension peg (connection peg). With one motor, the extension peg and the expansile hole can work. The expansile hole mainly consists of two connecting grippers, one cover, one sleeve, one track and one screw rod (Fig. 2 b). The hole can open and change its shape when its neighboring module is faulty and it needs to disconnect from the faulty module and finish the self-repairing action. When the connection/ disconnection appears among normal modules, the expansile hole does not open. When a normal module wants to disconnect from the faulty module, the hole of the normal module is open and disconnects from the faulty module. When a normal module wants to connect to the faulty module, the hole of the normal module is open and connects to the faulty module.

The extension peg mainly consists of three beads, a pin, a shell and a piston (Fig. 2 c). The hole can accept and lock the incoming peg by meanings of three beads. The hole can release a lock by releasing the beads of a normal module or open the hole when its neighboring module is faulty.



(a) M-Cubes module

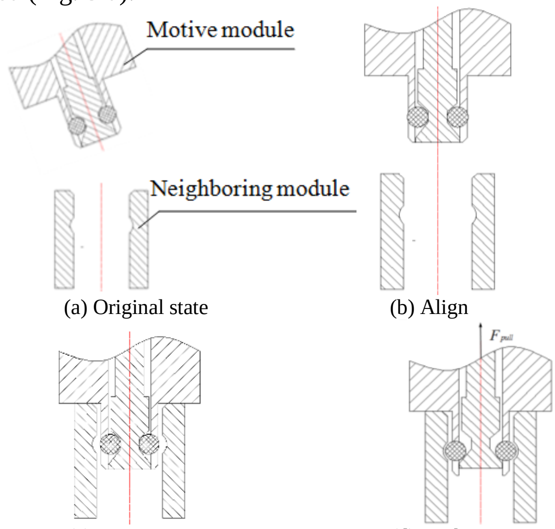
(b) One expansile hole (c) One extension peg

Figure 2. The diagram of M-Cube module.

III. ANALYSIS OF PROCESS

A. Docking Process

Docking process is shown in Fig. 3. First, according to the environment and task information, the motive module rotates about the fixed base (Fig. 3 a). Second, a rotary arm of the motive module rotates. The peg on the rotary arm is aligned to the hole on the neighboring module (Fig. 3 b). Driven by the motor, the pegs with pins insert into the corresponding holes. The pegs sit on the faces of holes in Fig. 3 c. The driven force *F*pull works, the pins move and the pegs are rest. Then beads are pushed out by the pins. Beads stick in the holes. So the pegs are locked in the holes. The docking of two neighboring modules is finished (Fig. 3 d).



(a) Original state (b) Align

(c) Insert (d) Lock

Figure 3. Docking process.

B. The States of the Docking

According the analysis of the docking process, the docking action is that one peg of motive module *i* inserts one hole of neighboring module *j*, and at the same time one peg of neighboring module *j* inserts one hole of motive module *i*. It is a complicated dual peg-in-hole process.

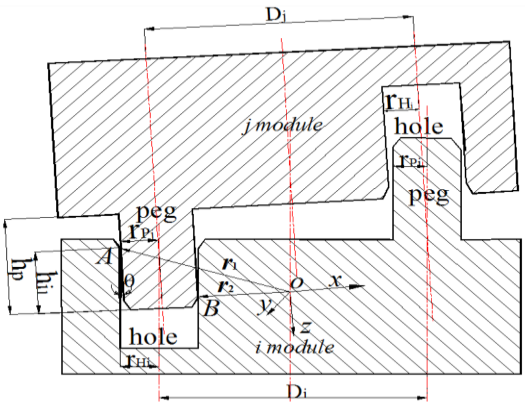


Figure 4. Two-point contact state in the left peg-in-hole

In the paper, two dimensional problems are discussed. The geometric models of one peg and one hole in module *i* and module *j* are shown in Fig. 4. We make the assumption: there exits tilt angle θ between two modules. If module *j* tilts to the left and there are two contact points in the left peg and the left hole, we can obtain

$$h_{i1}\sin\theta + 2r_{P_j}\cos\theta = 2r_{H_i} \tag{1}$$

When

$$h_{i1}\cos\theta = 2r_{P_j}\sin\theta \tag{2}$$

The boundary state of the docking can be obtained in Fig. 5. And the boundary angle is

$$\theta_0 = \arccos\left(\frac{r_{P_j}}{r_{H_i}}\right) \tag{3}$$

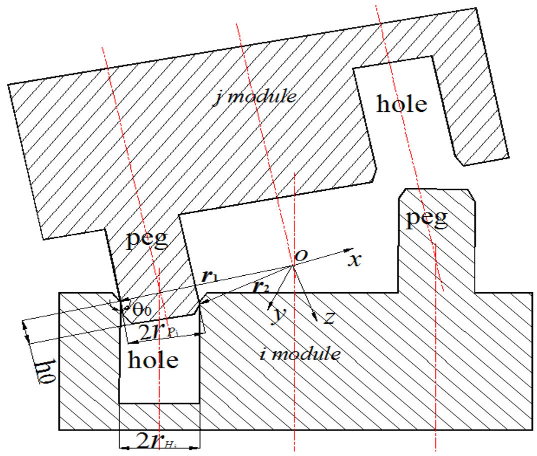
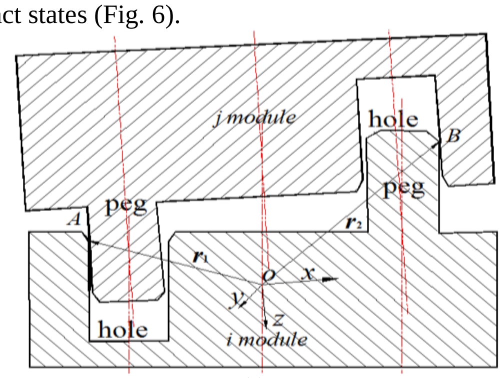
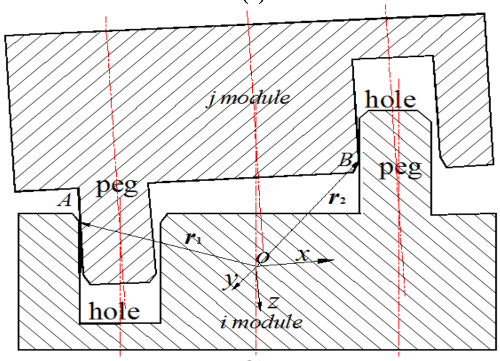


Figure 5. The boundary state of the docking.

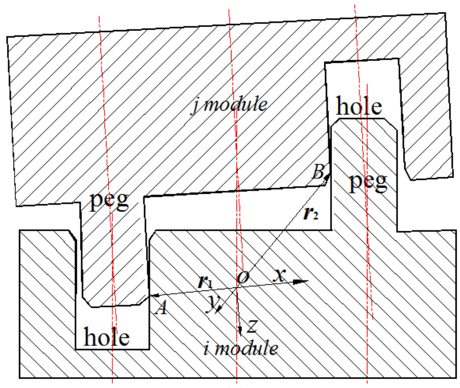
When θ is more than θ_0, two modules cannot align. Pegs cannot insert into holes. They cannot finish the docking process. So, the tilt angle must be adjusted to make $\theta << \theta_0$ and avoid sticking. When $\theta < \theta_0$, because the uncertainty of geometry and control, contact states exist during two modules docking. If module *j* tilts to the left, the hole of module *i* and that of module *j* all have one contact point respectively, there are four kinds of contact states (Fig. 6).



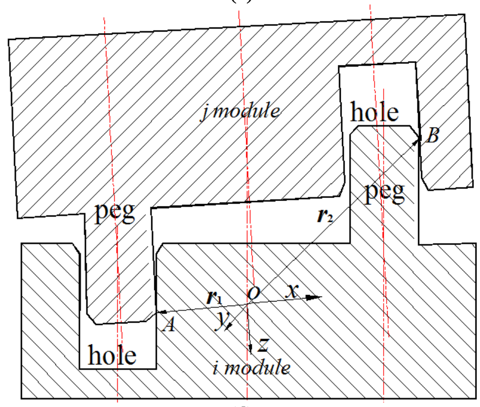
(a)



(b)



(c)



(d)

Figure 6. Two points contact states

For Fig. 6 a, which is shown in Fig.7 in detail, its geometric constraint is:

$$(h_P - h_{i1})\sin\theta + D_i + r_{H_i} + r_{P_j} = \left(D_j + r_{H_j} + r_{P_i}\right)\cos\theta \tag{4}$$

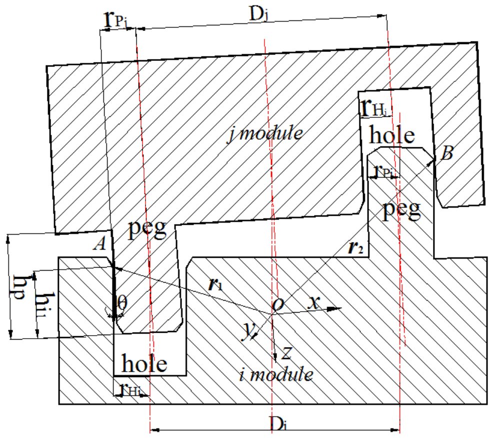


Figure 7. Geometric analysis of two-point contact state

If Equations (1) and (4) have one solution at least, a three-point contact state can be reached. A three-point contact state is relative to the geometry of two modules. It is transient. From the geometry constraints, we know there are at most four–point contact states (Fig. 8). The geometric constraint of two-point contact state in the left peg and the left hole is

$$h_{i1}\sin\theta + 2r_{P_j}\cos\theta = 2r_{H_i} \tag{5}$$

The geometric constraint of two-point contact states in the right peg and the right hole is

$$h_{j1}\sin\theta + 2r_{P_i}\cos\theta = 2r_{H_j} \tag{6}$$

The dimensions of two modules are the same. We can obtain

$$r_{P_i} = r_{P_j},\ \ r_{H_i} = r_{H_j} \tag{7}$$

Thus, when $h_{i1} = h_{j1}$, there are two-point contact states in the right peg and the right hole. Thus, there are at most four–point contact states in two modules docking. The pose of motive module should be adjusted and the tilt angle should be reduced to avoid appearing contact states.

where h_{i1} is an insertion depth of the left peg (module M_j) into the left hole (module M_i); h_{j1} is an insertion depth of the right peg (module M_i) into the right hole (module M_j). The peg of module M_j has a radius of r_{P_j}, whereas the peg of module M_i has a radius of r_{P_i}. The radii of one hole in module M_i and one hole in module M_j are r_{H_i} and r_{H_j}, respectively. θ and θ_0 are angles between the axes of a peg and a hole. D_i, D_j represent the distance between peg's axis and hole's axis of module M_i, module M_j, respectively.

From the above analysis, we know that the docking process of two modules is a complicated multiple peg-in-hole process. The pose of a motive module should be adjusted to make two modules align to finish the docking.

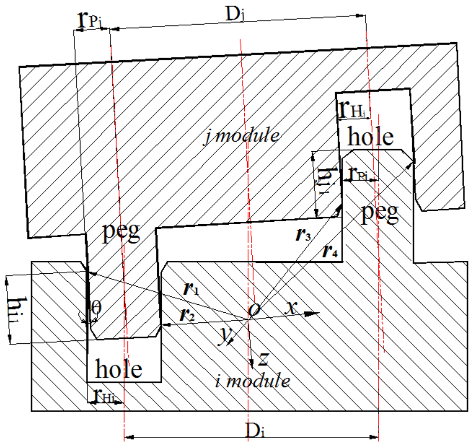
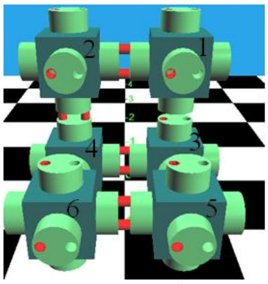


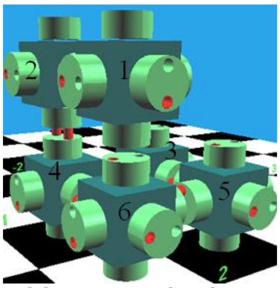
Figure 8. The geometric model of four–point contact state

IV. SIMULATION

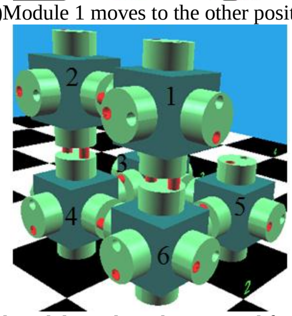
A simulation of the docking process on a six-module system is shown in Fig. 9. First, the module 2 connects to the module 4 and the module 1 connects to the module 2. The module 1 disconnects from the module 3 (Fig. 9 a). The module 2 rotates 90° around its center line and the module 1 moves to the other position (Fig. 9 b). Then, the module 1 and the module 6 finish their docking process (Fig. 9 c). When they finish their docking action, the module 2 disconnects from the module 4. The module 2 and the module 1 rotate 90° around the docking axis of the module 1 and the module 6. Thus, the module 2 moves to the other position (Fig. 9 d). The module 1 disconnects from the module 6 (Fig. 9 e). The module 2 and the module 1 rotate 90° around the docking axis of the module 2 and the module 5. Then, the module 1 connects to the module 3. The module 2 and the module 1 rotate 90° around the docking axis of the module 1 and the module 3 (Fig. 9 f). The connection and the disconnection between modules are finished.



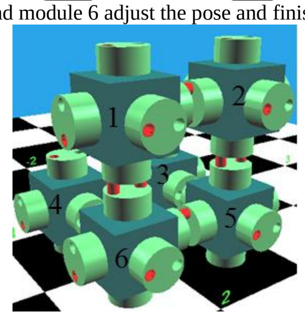
(a)Module 1 disconnects from module 3



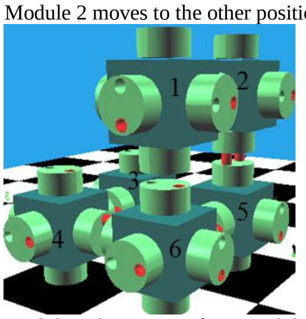
(b)Module 1 moves to the other position



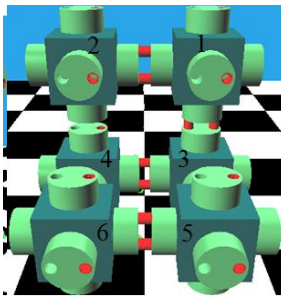
(c) Module 1and module 6 adjust the pose and finish their docking



(d) Module 2 moves to the other position



(e) Module 1 disconnects from module 6



(a) Go back to their original configuration

Figure 9. The simulation of the docking process on a six-module system

V. Conclusion

In this paper, the lattice self-reconfigurable robot is designed which can finish the self-repairing action. Each module consists of a central cube and six rotary arms. Each rotary arm consists of one expansile hole and one extension peg. Then, the states of docking and constraint between two modules are analyzed with the geometric method. At last, a simulation of six-module is shown that the modules can finish the docking process effectively.

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References

[1] M. Yim, W. M. Shen, B. Salemi, D. Rus, M. Moll, *et al.*, "Modular self-reconfigurable robot systems," *IEEE Robotics Automation Magazine*, vol. 14, no. 1, pp. 43-52, 2007.

[2] P. Dasgupta, V. Ufimtsev, C. Nelson, and S. G. M. Hossain, "Self-reconfiguration in modular robots using coalition games with uncertainty," *AAAI Workshop on Autonomous Action Planning for Autonomous Mobile Robots*, 2011, pp. 57-63.

[3] K. C. Cheung, E. D. Demaine, J. R. Bachrach, and S. Griffith, "Programmable assembly with universally foldable strings (moteins)," *IEEE Transactions on Robotics*, vol. 27, no. 4, pp. 718-729, 2011.

[4] S. Murata, E. Yoshida, H. Kurokawa, K. Tomita, and S. Kokaji, "Self-repairing mechanical systems," *Autonomous Robots*, vol. 10, pp. 7-21, 2001.

[5] S. Murata, H. Kurakawa, E. Yoshida, K. Tomita, and S. Kokaji, "A 3-D self-reconfigurable structure," in *Proc. IEEE International Conference on Robotics and Automation*, 1998, pp. 432-439.

[6] D. J. Christensen and K. Stoy, "Selecting a meta-module to shape-change the ATRON self-reconfigurable robot," in *Proc. IEEE International Conference Robotics and Automation*, Orlando, Florida, USA, 2006, pp. 2532-2538.

[7] Z. Bulter and D. Rus, "Distributed planning and control for modular robots with unit-compressible modules," *The International Journal of Robotics Research*, vol. 22, no. 9, pp. 699-715, 2003.

[8] B. Kirby, J. D. Campbell, B. Aksak, P. S. Pillai, J. F. Hoburg, T. C. Mowry, and S. C. Goldstein, "Catoms: Moving robots without moving parts," in *Proc. 20th National Conference on Artificial Intelligence*, vol. 4, 2005, pp. 1730-1731.

[9] Y. Q. Fei, "Docking design of self-reconfigurable robot," *International Journal of Advanced Robotic Systems*, vol. 8, no. 5, pp. 1-8, 2011.

[10] Y. Q. Fei, Y. L. Zhu, and P. Xia, "Analysis on self-morphing process of self-reconfigurable modular robot," *International Journal of Advanced Robotic Systems*, vol. 6, no. 3, pp. 215-222, 2009.

[11] A. Sproewitz, S. Pouya, S. Bonardi, J. Kieboom, R. Mockel, *et al.*, "Roombots: Reconfigurable robots for adaptive furniture," *IEEE Computational Intelligence Magazine*, vol. 5, no. 3, pp. 20-32, 2010.

[12] J. Davey, N. Kwok, and M. Yim, "Emulating self-reconfigurable robots - design of the SMORES system," in *Proc. IEEE/RSJ International Conference on Intelligent Robots and Systems*, Vilamoura, Algarve, Portugal. October 7-12, 2012, pp. 4464-4469.

Yanqiong Fei received the M. Eng. Degree in Southeast University, Nanjing, Jiangsu, China, in 1998, and the Ph.D. degree in Shanghai Jiaotong University, Shanghai, China, in 2002. Since 2002, she has been an Associate Professor with the Research Institute of Robotics, Shanghai Jiaotong University, Shanghai, China. Her research interests include robotics, self-reconfigurable modular robots, assembly system, etc.

