Ant3DBot: A Modular Self-reconfigurable Robot with Multiple Configurations

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Abstract. In the paper, a novel modular self-assembling and self-reconfiguring robot named Ant3DBot was proposed, which has many configurations. Ant3DBot consists of four semicircular iron spheroid shells, telescopic legs, and internal magnets that can rotate around the center. Ant3DBot can expand its shells and legs through a single motor, a synchronous belt and compressed springs, which results in two different docking states. Ant3DBot which has the height of 12 cm can traverse obstacles with the height of 8 cm, and pass through a 25° slope in extending configuration. For many unstructured environments, the cooperation of multiple Ant3DBots can reach a target point with simple control. The simulations show the basic ability of a single module to overcome obstacles as well as the cooperative motion of multiple robots. The results demonstrate that the Ant3DBot system has excellent locomotion performance and versatility.

Keywords: Modular robot · Self-reconfigurable robot · Continuous docking form · Fixed location docking form

1 Introduction

Modular self-reconfigurable robot (MSRR) has become a research hotspot in recent years [1–6]. Due to its unique reconfiguration strategy, it can turn into different configurations according to the tasks. Thus, it has high robustness and great adaptability, which is quite suitable for exploring unstructured environments and performing related tasks.

Connector is one of the basic components in MSRR system. Many innovative connectors have been proposed in previous studies. For example, the latches [3, 7], and hooks [8, 9] that are activated by shape memory alloys (SMA) or DC motors [1, 3], electromagnet [10], and permanent magnets [2, 11]. When they self-assemble, the modules need to plan their trajectories to align with the connectors, and require point-to-point connection. In fact, the connections between modules are time-consuming and have a low success rate.

A new type of connectors has emerged, namely, the freeform connector. MSRR with freeform connector can connect to each other without precise docking. However, most are limited to 2D plane movement [12–14]. To our knowledge, only four modular

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robots have demonstrated the ability of 3D continuous connection, namely, FireAnt3D [15], FreeBot [16], FreeSN [17] and SnailBot [18]. FireAnt3D requires large electric power consumption, has short service life and is time-consuming. FreeSN and SnailBot make up for the problem of FreeBot's single-point topology constraints, but they have weak movement ability in single form, and basically can only move on the plane. When performing tasks on unstructured environments, their overall speed is greatly reduced due to the self-reconfiguration (SR) process. While in reality, speed is a of high priority in the rescue of fire, earthquake and mining disaster, reconnaissance and other tasks [19, 20].

Currently, there are fewer researches on the deformation of single self-reconfigurable robots, and their connection form is simple. This paper aims to explore the deformation of single self-reconfigurable robot by itself to realize two kinds of connection form, and enhance obstacle crossing ability to complete more tasks faster.

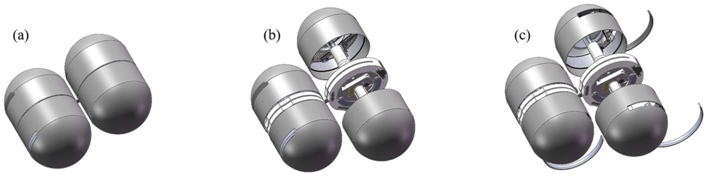

Fig. 1. Three configurations of Ant3DBot (Form I, II, and III).

Inspired by the anatomy of ants, a novel MSRR named Ant3DBot was proposed in this paper, as shown in Fig. 1. It consists of four semicircle iron spherical shells, retractable legs and internal Magnet that rotates around its center. Unlike the existing modular self-reconfigurable robots with only one connection form, Ant3DBot can control the expansion of both spherical shells and the upper legs through a single motor combined with a synchronous belt and compressed springs. When the spherical shells are not extended, as shown in Fig. 1(a), Ant3DBot uses 3D continuous docking points to attach to its peers regardless of alignment, thus docking becomes more convenient and free. When the spherical shells are extended, as shown in Fig. 1(b), dock-to-dock alignment can also be used to improve connection strength. Furthermore, its single obstacle crossing capability is worth mentioning. After the leg extension, a single Ant3DBot with the height of 12 cm can cross over obstacles with the height of 8 cm, and slope of 25°. Figure 1 shows the three configurations of Ant3DBot. It should be noted that the transition between the three configurations can also be achieved.

This paper is organized as follows: Sect. 2 introduces the mechanical design; Sect. 3 and Sect. 4 introduces the movement and simulation results of Ant3DBot, respectively. Finally, Sect. 5 gives the conclusions and future work.

2 Mechanical Design

2.1 Ant3DBot Design

Figure 2 shows the view of Ant3DBot in its expansion form. Ant3DBot consists of two spheroid shells equipped with internal magnets. It is mainly composed of four parts, namely, iron spheroid shell, shell driving structure, internal magnet driving structure and shell expansion structure. It should be noted that in this design, the positions that the front shells can reach are different from those of the back shells ($d_f = 70$ mm, $d_r = 11$ mm). Similarly, the reaching positions of front and back legs are also different ($L_f = 124.01$ mm, $L_{fmax} = 131.6$ mm, $L_r = 88.96$ mm, $L_{rmax} = 100.65$ mm), as shown in Fig. 3.

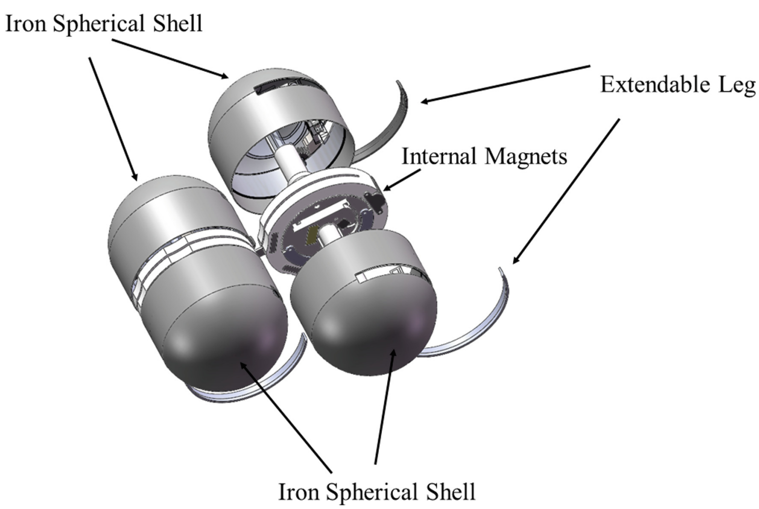

Fig. 2. The configuration of Ant3DBot when its legs are fully expanded.

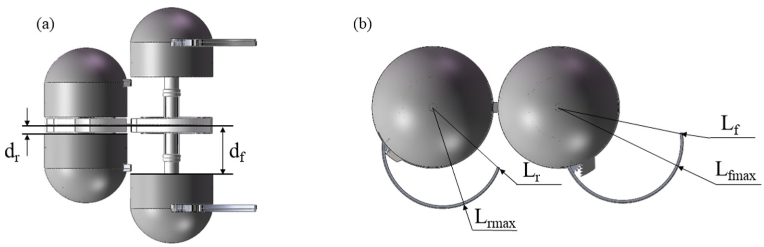

Fig. 3. Top view and side view of Ant3DBot when its legs are fully expanded.

The shell is mainly composed of iron spherical shell and extendable legs. The shell driving structure consists of two motors which control the rotation of the robot axes on both sides respectively through the gearbox and the gears, thereby driving the rotation of the spherical shell and realizing the forward movement, backward movement or rotation. The internal magnet movement is driven by a DC motor through a set of internal meshing gears. It can drive the permanent magnet to rotate about 300 degrees along the axis of the spherical shell ($\theta = 60°$), as shown in Fig. 4.

The expansion of the shell is driven by the synchronous belt on both sides of the transmission rod, and the compressed spring in the spherical shell, through a single motor. It can control the expansion of the spherical shell on both sides as well as the expansion and retraction of the upper legs, as shown in Fig. 5.

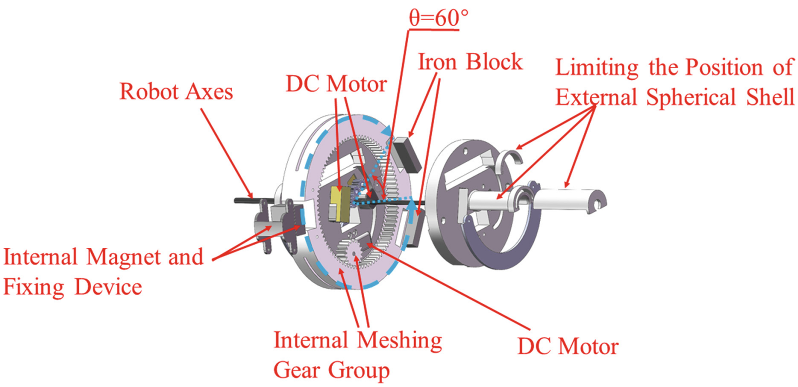

Fig. 4. Shell driving structure and internal magnet driving structure.

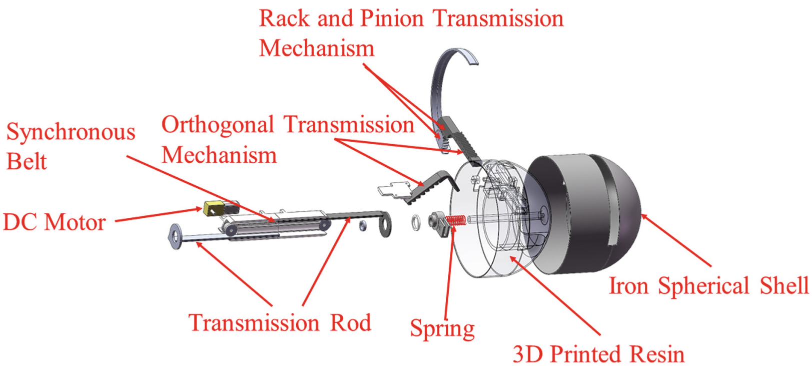

Fig. 5. Expansion and retraction structure of the shell and the legs.

The shell and leg expansion process of Ant3DBot is shown in Fig. 6. The initial conditions are as follows: the spring is compressed during assembly, so that the elastic force of the initial spring is slightly greater than the frictional force between the shell and the ground, and the spring can be further compressed by 20mm to drive the expansion of the leg. The detailed process is as follows. First, the synchronous belt drives the connecting rod compression spring. When the elastic force of the compression spring is greater than the frictional force between the shell and the ground, the connecting rod will drive the spherical shell outward. When the spherical shell expands outward for a certain distance, as shown in Fig. 3(a), it will be constrained by the position of the internal structure, and the continuous motion of the synchronous belt will drive the connecting rod compression spring. At the same time, the compression spring will be driven by the orthogonal transmission mechanism and the rack and pinion transmission mechanism to expand the legs. Based on the above analysis, when there is smaller external resistance, the selection of appropriate springs can ensure that the spherical shell extends at first, and the legs extend later.

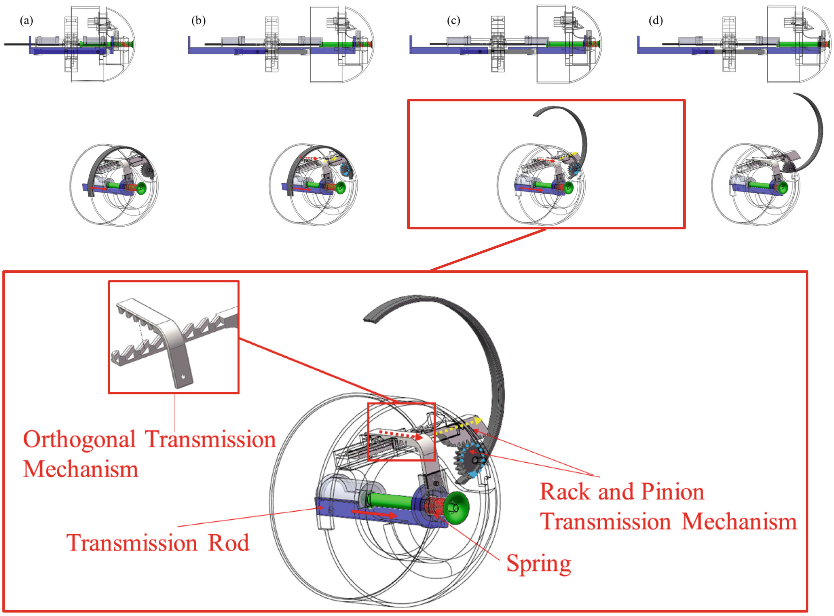

Fig. 6. The expansion process of the robot shell and the legs.

In fact, the expansion is a very useful function. For example, when the robot is stuck in a dilemma and cannot expand the spherical shell, that is, when the external resistance is very large, the movement of the synchronous belt will first compress the spring and drive the expansion of the legs, thus smoothly helping the robot to escape from the trapped ground.

Single Ant3DBot has strong barrier crossing capability because it can control the outward extension and leg expansion of the spheroid shell. Simulation experiments show that single Ant3DBot with the height of 12 cm can cross over 8 cm high obstacles and 25° ramp after extending legs. In addition, the position of the internal magnets in the spheroid shell is controlled by the motor. Besides, it can control the outward extension and leg expansion of the shells. Ant3DBot has many docking modes, including both FreeBot and chain structures, which will be discussed in the third part.

2.2 Connector

FreeBot can achieve fast 3D continuous docking by using a permanent magnet and an iron sphere. Ant3DBot in Form I is similar to FreeBot in that it contains magnets embedded in the body, can rotate around the center, and connect peers. The 3D continuous docking mechanism is one of the most important mechanisms of freeform MSRR.

Notably, compared with FreeBot, Ant3DBot is indeed more difficult to rotate in peers. However, it still has advantages in Form I when this is a genderless connector and the connection of two Ant3DBots can be at almost any point on their spherical iron shell, and it is sufficient when performing refactoring and loading functions.

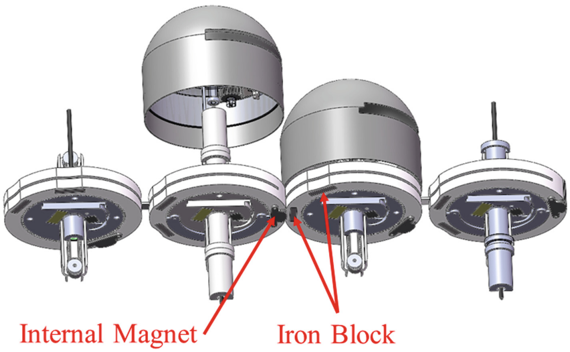

Fig. 7. Connectors of Ant3DBot in Form II.

In Form II, Ant3DBot can be linked with other Ant3DBots by a chain, as shown in Fig. 7. Thereby, Ant3DBot can pass through obstacles such as a gap and overcome higher obstacles, which will be explained in the fourth Part of experimental results.

The specifications of the magnet and the thickness of the iron shell of Ant3DBot in Form I are consistent with that of FreeBot. Therefore, the force action is no longer analyzed in this paper. The connectors of Ant3DBot in Form II can easily adjust the size of the iron block to change the connection strength according to the required connection strength of the tasks, so it is no longer analyzed.

3 Motion of Ant3DBot

3.1 Individual Motion

Each Ant3DBot module contains 8 motors, and has the same front and rear structures, including 4 motors in each. The available motions are summarized according to their functions, as shown below.

1) Connection: Ant3DBot is connected to the peers by rotating the magnet position. The magnet position can be adjusted in advance for rapid connection. The front and rear motors control two magnets respectively.
2) Disconnection: Ant3DBot rotates the magnet position until it disconnects from its peers.
3) Rotation: Both sides of the motors (DC motors) rotate in opposite directions respectively.

4) Driving: When the iron shell contacts with an external environment such as the ground, it can rotate to provide driving force. The four spherical shells are controlled by four motors respectively.
5) Extension and retraction: one motor can control the expansion and retraction of both sides of spherical shells and legs; two motors control the expansion and retraction of the four spherical shells and legs.

3.2 Connection and Separation

In order to make the modular robots realize self-assembly and self-reconfiguration, a single modular robot needs to be able to attach and detach itself from its peers. Besides, it necessarily has the ability to move on other modules. Two basic actions (namely, connection and separation) were defined for a single modular robot.

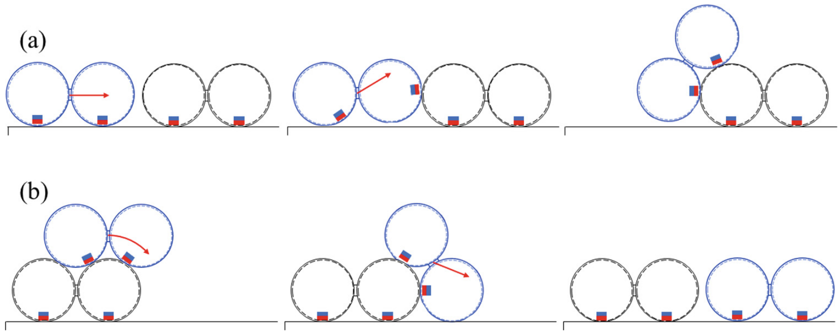

Fig. 8. Connection and separation of Ant3DBot in Form I.

The connection and separation of Ant3DBot in Form I enable the modular robot group to self-assemble (see Fig. 8). And the connection and separation only occur when the robot is about to touch or leave the ground. The connection and separation of Ant3DBot in Form II is shown in Fig. 9.

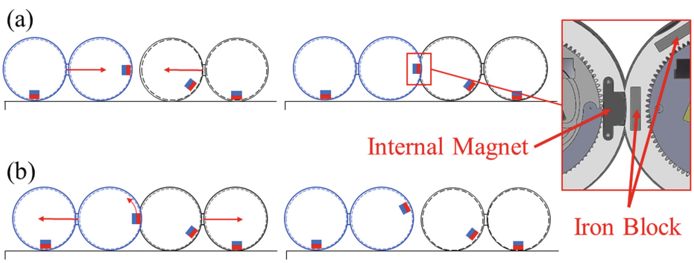

Fig. 9. Connection and separation of Ant3DBot in Form II.

3.3 Reconfiguration

The collaboration of multiple Ant3DBot showed some exciting performance. For the MSRR system, we focused on how to rearrange these modules into different configurations. Ant3DBot can crawl on the surfaces of other Ant3DBots and connect to other Ant3DBots when spherical shells are expanded so as to achieve many reconfigurable functions.

Adjacent transition and nonadjacent transition are usually performed in 3D space, meaning that moving robots can have various postures. For simplicity, only one of these cases was drawn in Fig. 10(a) and Fig. 10(b) respectively.

It was exciting to note that Ant3DBot could achieve any connection in Form I and achieve point-to-point connection in Form II, so it could excellently perform extremely difficult tasks. As shown in Fig. 11, the black is the connection of two Ant3DBots in Form II; the blue is that of the Ant3DBot in Form I. The red represents the movement process of Ant3DBot in Form I, and the green dashed lines roughly describe the movement trajectory of the red Ant3DBot.

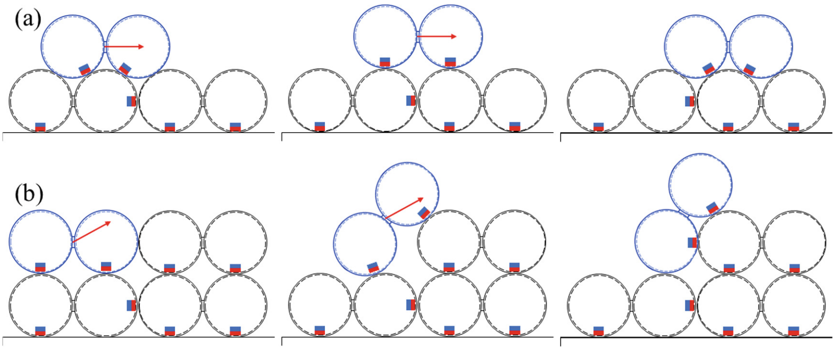

Fig. 10. Adjacent transition and nonadjacent transition of Ant3DBot in Form I.

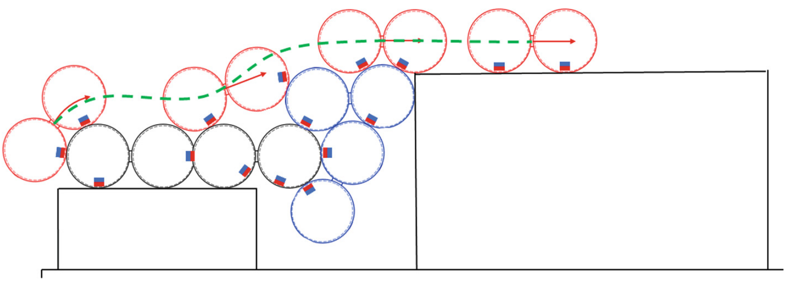

Fig. 11. Multiple Ant3DBot to form a bridge to pass through a gap.

4 Simulation Results

Simulations were performed in CoppeliaSim. They demonstrated the kinematic capabilities of Ant3DBot, including various basic actions and cooperative movements of multiple modules.

4.1 Performance of Single Ant3DBot

Figure 12 shows the basic abilities of a single modular robot. Although the specific initial position of the Ant3DBot for crossing 8 cm obstacles was required, the single modular robot still had the outstanding ability of crossing obstacles with 0.66 times its own height.

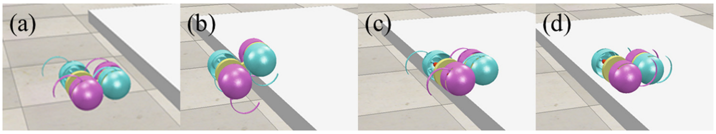

Fig. 12. A single modular robot to cross over obstacles with the height of 8 cm

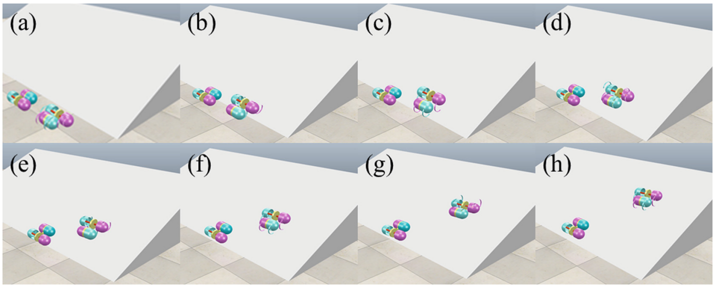

Fig. 13. A single modular robot to climb a 25° Slope

Figure 13 shows a single modular robot crossing over a 25° slope. In Fig. 13, two Ant3DBot robots were the same Ant3DBot in Form II and in Form III, respectively. According to the results, it can be seen that the Ant3DBot in Form III could rapidly climb the 25° slope. However, the Ant3DBot in Form II could not go further upward after reaching the middle of the slope.

4.2 Two Ant3DBots to Collaborate to Pass Through a Gap with the Width of 20 cm

Figure 14 shows two Ant3DBots in Form II collaborating to cross a gap with the width of 20 cm. The two Ant3DBots had a total length of about 50 cm, which could cross a gap with the width of 20 cm as quickly as they did in flat land. For the gap obstacles shown in Fig. 14, multiple Ant3DBots in Form II could coordinate and pass through it with almost no decrease of velocity.

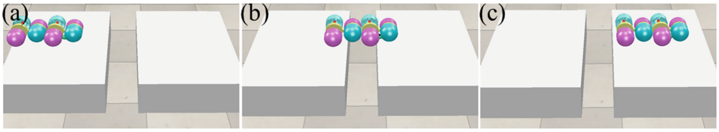

Fig. 14. Two Ant3DBots to collaborate to cross a gap with the width of 20 cm.

4.3 Two Ant3DBots to Collaborate to Cross a Step with the height of 10 cm

Figure 15 shows two Ant3DBots synergistically moving through a step with the height of 10 cm. Each Ant3DBot only extended two legs, being an intermediate form between Form II and III. In addition, there were numerous Ant3DBot and Ant3DBot forms available for exploration between Form II and III. They could pass through with basically no loss of velocity under multiple obstacles. The collaborated movement mode in Form I was not considered unless Ant3DBots in Form II and III, and their intermediate forms are unable to pass the obstacles.

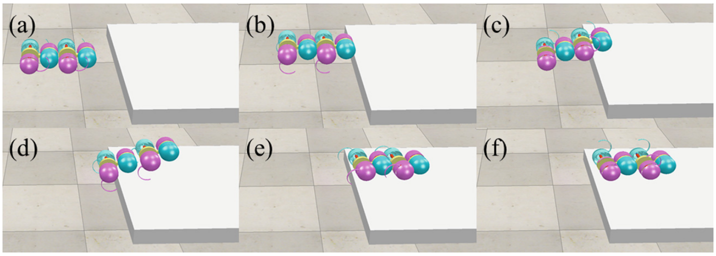

Fig. 15. Two Ant3DBots to collaborate to pass through a step with the height of 10 cm.

4.4 Loading Experiment

All forms of the Ant3DBot were non-sealing structures. They could be point-to point connected and crawl on the surface of other Ant3DBot. Thus, they were highly suitable for fulfilling the loading tasks. Therefore, partial custom-made containers, a 2mm diameter string or objects with hoses could be placed in the position shown in Fig. 16.

Fig. 16. Loading experiment of Ant3DBots.

5 Conclusions and Future Work

In this paper, a bio-inspired modular self-reconfiguring robot named Ant3DBot is proposed, which has many configurations and can move in multiple forms. The motor equipped in the Ant3DBot can control the expansion and retraction of both sides of spherical shells and legs. Single Ant3DBot can cross over 8 cm high obstacles and 25° ramps. Ant3DBot in Form I uses the 3D continuous dock to attach to its peers regardless of alignment. In Form II and III, Ant3DBot is linked by fixed docking locations and can coordinate to pass through gaps and steps. Its potential has been proved by simulations.

In the future, we will explore more possibilities based on the performance of Ant3DBot, and design self-reconfiguration algorithms and motion planning algorithms suitable for it according to its characteristics, and conduct related testing in more complex scenarios.

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References

1. Kurokawa, H., et al.: Distributed self-reconfiguration of M-TRAN III modular robotic system. The Int. J. Roboti. Res. **27**(3–4), 373–386 (2008)
2. Davey, J., Kwok, N., Yim, M.: Emulating self-reconfigurable robots-design of the SMORES system. In: IEEE/RSJ International Conference on Intelligent Robots and Systems 2012, IEEE, pp. 4464–4469 (2012)
3. Spröwitz, A., et al: Roombots: reconfigurable robots for adaptive furniture. IEEE Computational Intelligence Magazine **5**, 20–32 (2010)
4. Seo, J., Paik, J., Yim, M.: Modular reconfigurable robotics. Annual Review of Control, Robotics, and Autonomous Systems **2**, 63–88 (2019)
5. Liu, C., Yim, M.: Reconfiguration motion planning for variable topology truss. In: IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) 2019, IEEE, pp. 1941–1948 (2019)
6. Liu, C., Yu, S., Yim, M.: A fast configuration space algorithm for variable topology truss modular robots. In: IEEE International Conference on Robotics and Automation (ICRA) 2020, IEEE, pp. 8260–8266 (2020)
7. Salemi, B., Moll, M., Shen, W. M.: SUPERBOT: a deployable, multi-functional, and modular self-reconfigurable robotic system. In: IEEE/RSJ International Conference on Intelligent Robots and Systems 2020, IEEE, pp. 3636–3641 (2006)
8. Jorgensen, M.W., Ostergaard, E.H., Lund, H.H.: Modular ATRON: modules for a self-reconfigurable robot. In: IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) (IEEE Cat. No. 04CH37566) 2004, IEEE, vol. 2, pp. 2068–2073 (2004)
9. Wei, H., et al.: Sambot: a self-assembly modular robot system. IEEE/ASME Trans. Mechatron. **16**(4), 745–757 (2010)
10. Zykov, V., et al.: Evolved and designed self-reproducing modular robotics. IEEE Trans. Rob. **23**(2), 308–319 (2007)

11. Tosun, T., et al.: Design and characterization of the ep-face connector. In: IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) 2016, IEEE, pp. 45–51 (2016)
12. Li, S., et al.: Particle robotics based on statistical mechanics of loosely coupled components. Nature **567**(7748), 361–365 (2019)
13. Shimizu, M., Ishiguro, A.: An amoeboid modular robot that exhibits real-time adaptive reconfiguration. In: IEEE/RSJ International Conference on Intelligent Robots and Systems 2009, IEEE, pp. 1496–1501 (2009)
14. Malley, M., et al.: Eciton robotica: design and algorithms for an adaptive self-assembling soft robot collective. In: IEEE International Conference on Robotics and Automation (ICRA) 2020, IEEE, pp. 4565–4571 (2020)
15. Swissler, P., Rubenstein, M.: FireAnt3D: a 3D self-climbing robot towards non-latticed robotic self-assembly. In: IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) 2020, IEEE, pp. 3340–3347 (2020)
16. Liang, G., et al.: FreeBot: a freeform modular self-reconfigurable robot with arbitrary connection point-design and implementation. In: IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) 2020, IEEE, pp. 6506–6513 (2020)
17. Tu, Y., Liang, G., Lam, T.L.: FreeSN: a freeform strut-node structured modular self-reconfigurable robot-design and implementation. In: IEEE International Conference on Robotics and Automation (ICRA) 2022, IEEE (2022)
18. Zhao, D., Lam, T.L.: SnailBot: a continuously dockable modular self-reconfigurable robot using rocker-bogie suspension. In: IEEE International Conference on Robotics and Automation (ICRA) 2022, IEEE (2022)
19. Luo, H., Lam, T.L.: Adaptive flow planning of modular spherical robot considering static gravity stability. IEEE Robotics and Automation Letters **7**(2), 4228–4235 (2022)
20. Luo, H., et al.: An obstacle-crossing strategy based on the fast self-reconfiguration for modular sphere robots. In: IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) 2020, IEEE, pp. 3296–3303 (2020)