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Sambot: A Self-assembly Modular Robot for Swarm Robot

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Abstract—**This paper presents a novel self-assembly modular robot (Sambot) that also shares characteristics with self-reconfigurable and self-assembly and swarm robots. Each Sambot can move autonomously and connect with the others. Multiple Sambot can be self-assembled to form a robotic structure, which can be reconfigured into different configurable robots and can locomote. A novel mechanical design is described to realize function of autonomous motion and docking. Introducing embedded mechatronics integrated technology, whole actuators, sensors, microprocessors, power and communication unit are embedded in the module. The Sambot is compact and flexble, the overall size is 80×80×102mm. The preliminary self-assembly and self-reconfiguration of Sambot is discussed, and several possible configurations consisting of multiple Sambot are designed in simulation environment. At last, the experiment of self-assembly and self-reconfiguration and locomotion of multiple Sambot has been implemented.**

I. INTRODUCTION

In recent years, Self-reconfigurable robots has been more attention [3], [7]. Self-reconfigurable robot is made up of a group of autonomous robot modules that can connect and disconnect, and can autonomously change their shape and size to meet demands for environment and task. While in the research field of self-reconfigurable robots, the basic modules that form the self-reconfigurable robots usually do not move on their own or have very limited ability of autonomous locomotion. In some systems, the reconfiguration of the shape was demonstrated with the modules being pre-arranged at the pre-set positions.

Different from other self-reconfigurable robots, we proposed a novel self-assembly modular robot (Sambot), which is autonomous mobile robots with docking and reconfigurable function. Multiple Sambots can be self-assembled to form a robotic structure, which can reconfigure into different configurable robots.

Self-assembly is a process by which preexisting components autonomously organize into patterns or structures without human intervention [1]. Self-assembly is a general phenomenon in nature. For example, Ants can form chains composed of their own bodies which are used to pull leaves together to form a nest, or to bridge a passage between branches in a tree [13]. In robotics, self-assembly is the process by which many module are driven to connect into a larger robot that has greater capabilities than do the individual module [2]. For example, muiltple Sambot can form a robotic structure such as snake-like robot to crawl through a narrow passage and then to reconfigurable four-legged crawller to adapt the rough terrain. Therefore, this robots' ability in self-assembly and self-reconfigurable robot makes them particularly useful for applications in unstructured, remote and hazardous environment such as deep sea and space exploration, urban rescue, and military intelligence.

Additionally, multiple self-assembly modular robot actually formed a swarm of robots. Swarm robotics is consist of large numbers of mostly simple physical robots. Self-assembly is a new mode of swarm robotics' cooperation. Self-assembly characteristic of swarm robotics is similar to that of self-reconfigurable robots. Differently, the modules of the current self-reconfigurable robots are not capable of autonomous motion but they can realize metamorphism and reconfiguration depending on other modules, such as M-TRAN [4], PolyBot [11], CONRO [12] etc. However, each single robot module of swarm robotics with self-assembly characteristic can either move autonomously or connect with each other, such as swarm-Bot [6] etc. Actually, the combination of swarm robots, self-assembly robots and self-reconfigurable robots may provide important ways for manufacturing and designing engineerized robots with real practical functions, hence provide a basis for designing new robotic systems whose functions and morphologies can both evolve [14].

In previous studies, due to the size, degree of freedom, power and other design constraints, research challenges of self-reconfiguration and swarm robotics tend to be concentrated in mechanical design of the single module or the single robot. Up to now, the introduction on swarm robotics with both self-assembly and self-reconfigurable function is rarely found. Shen have proposed a self-reconfigurable robot SuperBot [5], which implemented decomposition and recombining of the robotic structure composed of several modules. A single SuperBot module has three degrees of freedom can move forward and turn, but the mobility is relatively limited.

The Sambot is a single robot moduler with both self-assembly and self-reconfigurable characteristic. A novel mechanical structure design makes Sambot either move autonomously and connect with the others. Introducing embedded mechatronics integrated technology, whole actuators, sensors, microprocessors, power and

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communication unit are embedded in the module. The Sambot is compact and flexble, the overall size is 80×80×102mm.

The paper is organized as follows. In section Ⅱ, design principle and overall structural design of Sambot is discussed. In section Ⅲ, mechanical design of Sambot robot is introduced. In section Ⅳ, electrical design of Sambot robot is described. In section Ⅴ, self-assembly and self-reconfiguration function of multiple Sambot is introduced. In section Ⅵ, some experiments on Sambots is done including autonomous docking and reconfiguration and locomotion. Conclusions and future work are given in the last section.

II. DESIGN PRINCIPLES

According to research work of Yim [3], [7] and Groß [6] etc, the existing reconfigurable robots can be divided into four kinds of architecture: chain-based, lattice-based, mobile and stochastic.

In this paper, the Sambot with both self-assembly and self-reconfigurable characteristic is similar to mobile and chain-based reconfigurable robot. Currently, some mobile reconfigurable robots has been proposed such as CEBOT [8], SMC(Super Mechano Colon) [9], Millibot [10], Swarm-Bots and so on. These robots are composed of homogenous and heterogeneous individual robots and two or more individual robots can connect together. Swarm-Bots can also demonstrate that multiple s-bots finish handling or crossing the barrier through self-assembly cooperation. However, due to structural design constraints, after these mobile reconfigurable robots are connected into a robotic structure, which does not have the capability of the locomotion and the reconfiguration similar to chain-based reconfigurable robots.

The Sambot is a self-assembly robot combining advantages of mobile and chain-based reconfigurable robot. That is, each Sambot module is a fully autonomous mobile robot that is similar to individual robot in swarm robot, while muitiple Sambot can construct a robotic structure such as snake-like robot or multi-legged crawller robot through self-assembly. The robotic structure has the ability locomotion and reconfiguration similar to chain-based reconfigurable robot. In order to achieve the above functions, Sambot must meet the following design requirements:

1) Autonomy: Each module is an autonomous mobile robot including the power supply, microprocessor, drives, sensors and communications unit.
2) Self-assembly: in order to realize the self-assembly, each Sambot should have active docking mechanism, so that it can realize autonomous connection and disconnection of two or more modules.
3) Motion Ability: the robotic structures assembled with multiple modules should have the locomotion same to that of chain-type reconfiguration robots.
4) Self-reconfiguration or self-metamorphic: the robotic structures assembled with multiple modules should have the ability of self-reconfiguration or self-metamorphic, i.e. transform from one robotic structure (e.g. a snake) to another robotic structure (e.g. a quadruped).

Based on the above design requirements, the outline design of the Sambot module is shown in Fig.1. Each Sambot module is an autonomous mobile robot including the power supply, microprocessor, sensors, drives, and wireless communication module. The overall size of Sambot module is 80×80×102 mm and the weight is 400 grams.

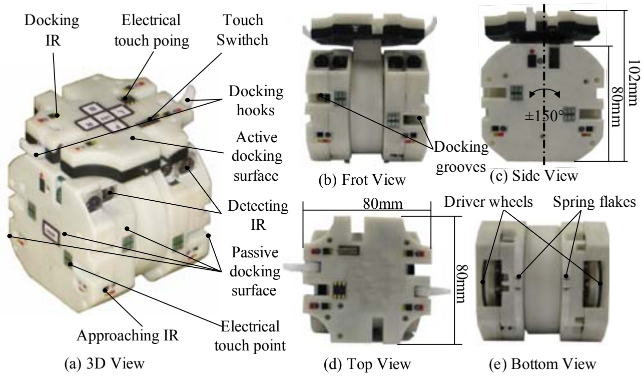

Fig.1. The general schematic diagram of the Sambot
(a) 3D View; (b) Front Viev; (c) Side View; (d) Bottom View

As shown in Fig. 1, the structure of Sambot is divided into an active docking surface and the autonomous mobile body. On the active docking surface there is a pair of active docking hooks, which can dock with the four docking grooves (front, back, left and right passive docking surface) on the autonomous mobile bodies of other Sambots. The mechanical design of the docking hooks and docking grooves allows two Sambots to realize autonomous docking and locking within some misalignment. At the active docking surface, there are 4 pairs of docking infrared sensors. On the upper part of the front and back of the autonomous mobile body are installed two pairs of detecting infrared sensors each, which are used to detect obstacles in front of the robot; on the lower part of the front, back, left and right side of the autonomous mobile body are two pairs of approach infrared sensors each, which, by reacting with the docking infrared sensors on the active docking surface of other Sambots, monitor the relative positions of the two Sambots and provide navigating information for the docking.

As shown in Fig. 1 (c), the active docking surface of Sambot can rotate around the central axle in a range of ±150º; when docking, the the active docking surface rotates 90º forward or backward, so as to make the active docking surface dock with the passive docking surface of other Sambot; after docking, the rotating joint can rotate around the central axle horizontally, so as to realize the locomotion of the robotic structure self-assembled with multiple Sambots.

After the docking of two Sambots, the six electric touch points on the active docking surface can be pressed tightly and fit with the six electric touch points on the passive surface. It is used as CAN bus communication and charging between Sambots after dockings. The main body of Sambot is driven by two symmetrical wheels on bottom. In addition, as shown in Fig.1 (e), on the inside of the wheels are installed a pair of spring flakes to ensure smoothness during the autonomous motion of Sambot.

III. MECHANICAL DESIGN

The mechanical parts of Sambot is manufactured with engineering plastic materials, which, while ensuring the strength of the structure, decreases the weight of the structure. Fig. 2 gives the exploded view of Sambot, demonstrating the connection of the parts of Sambot. As shown before, Sambot has four degree of freedoms, including the autonomous movement of the two differential driving wheels, the autonomous rotate of the active docking surface around the central axle of the main body, and the opening and closing of the docking hooks. The main body of Sambot is composed of two symmetrical halves (left and right) and the rotating mechanism of the active docking surface. At the bottom of each of the two halves is installed a driving wheel, which is driven by two motors after being decelerated by the decelerator, and on each of the driving wheel is installed a photoelectric encoder, which feeds back the speed and angle of the rotating wheel. After testing, the driving speed of Sambot ranges from 0~20cm/s, and it can also drive in the reverse direction.

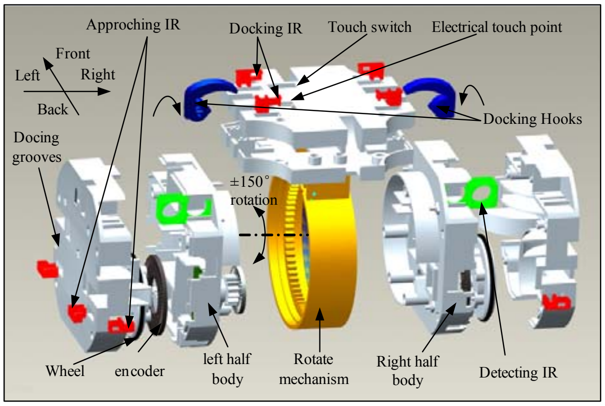

Fig.2. The exploded view of Sambot module

A. *The rotating mechanism*

The rotating mechanism of the active docking surface is realized through a set of gear mechanisms. As shown in Fig. 3, the rotating mechanism includes a motor, decelerator and a gear group meshed both inside and outside. The motor transmits rotating force through the outside gear to the inside gear, drives the docking surface fixed on the inside gear by screws to rotate. The rotating mechanism is compressed and fixed by the left and right halves. On the end of the axle of the rotating motor is installed a photoelectric encoder, which feeds back through angle position, and realizes control over the precisive position of the rotating docking surface. The torque transmitted by the motor through the driving mechanism can reach 1.5N·m, enough to lift two modules and to rotate.

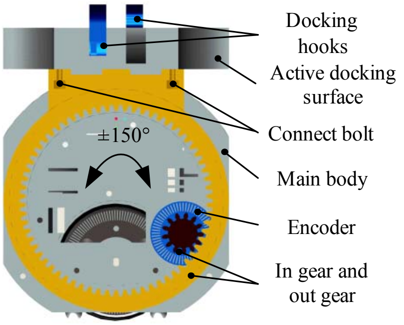

Fig.3. The rotating mechanism of active docking surface

B. *The rotating mechanism*

The rotating mechanism of the active docking surface is realized through a set of gear mechanisms. As shown in Fig. 3, the rotating mechanism includes a motor, decelerator and a gear group meshed both inside and outside. The motor transmits rotating force through the outside gear to the inside gear, drives the docking surface fixed on the inside gear by screws to rotate. The rotating mechanism is compressed and fixed by the left and right halves. On the end of the axle of the rotating motor is installed a photoelectric encoder, which feeds back through angle position, and realizes control over the precisive position of the rotating docking surface. The torque transmitted by the motor through the driving mechanism can reach 1.5N·m, enough to lift two modules and to rotate.

C. *Design of active docking mechanism*

When designing active docking mechanism, several requirements are needed to ensure: (1) it can detect other robot, and within certain distance realize the positioning and guiding of two robots; (2) it must have the ability of realizing docking within certain range of misalignment; (3) after the two modules are connected, the center distance between them should be as small as possible to reduce the rotational torque; (4) the adequate structural strength is needed to ensure the connection surface is not damaged in the connection phase and after connected; (5) the adequate reliability of connection is also needed to prevent separation of connected modules.

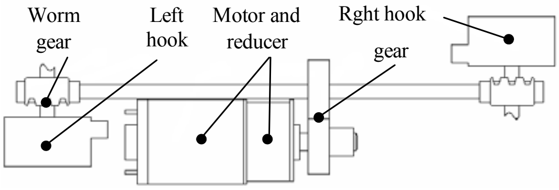

Fig.4 The mechanism of docking hooks

Sambot selects a worm-driven docking hook mechanism, which realizes connection through locking by active docking hooks with the docking grooves of another robot, and during the process of docking and disconnect, it occupies a small space and realizes zero gap disconnect. As shown in Fig. 4, the inside drive mechanism is as follows: the output of the motor is decelerate by a pair of gears and then transmitted to the turning axle, the ends of the turning axle are connected to worm gear, the worm gear and worm drives the hooks to rotate, and realize connection and disconnection.

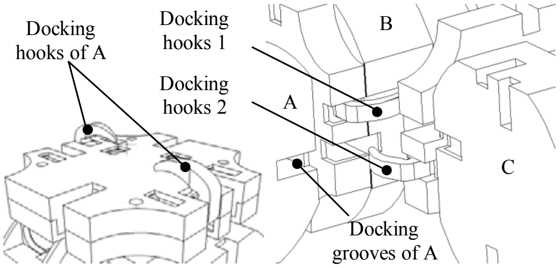

Fig.5 The arrangement of docking grooves

The docking groove adopts the asymmetrical arrangement, and allows synchronized docking of the front, back, left and rights sides without interference. As shown in Fig. 5, Sambot A and Sambot B are docked by Hook 1 (the boldface lines show the contact sides of Sambot A and Sambot B). Now Sambot C needs to be docked with Sambot B by Hook 2, to avoid interference, when Hook 2 rotates into the groove of Sambot B, there are also open grooves on the active docking surface of Sambot A, thus realizing the synchronized docking of multiple Sambots with the four sides of front, back, left and right without interference.

IV. ELECTRICAL DESIGN

The electric system of Sambot is shown is Fig.6, which can be divided into three units: the controlller unit, the sensor and actuator unit and the communication unit.

A. The control unit

This unit uses STM32 microprocessor of the ARM series as the main processor. The STM32 completes the robot's navigation localization and also the decision-making tasks. This unit can collect the information on gyroscope and accelerometer, and receive the encoder information through I2C interface. After periodically calculating with these information, the STM32 can complete the robot's localization. And the result can be used as a basis for navigation. On the other hand, with periodically collecting information on each sensor through I2C interface and based on the control algorithm in chip, this unit make decisions. At the same time, this unit can obtain the information from other robots by the global communication unit so that it can make task decision or response.

B. The sensor and actuator unit

This unit consists of controllers, sensors and executive unit. Inside the Sambot, there are four micro DC motors Separately for as the left wheel drive motor, the right wheel drive motor, the docking platform rotating motor, as well as the docking hook motor. Each motor is controlled by a separate ATMega8 microcontroller for driving, and the ATMega8 also complete the encoder and sensor information collection. The main-control chip connects with these ATMega8s through a I2C serial communication pattern named "one master and four slavers". ATMega8 returns the sensor information when based on the read command from master, and executes the corresponding motor control based on the write command.

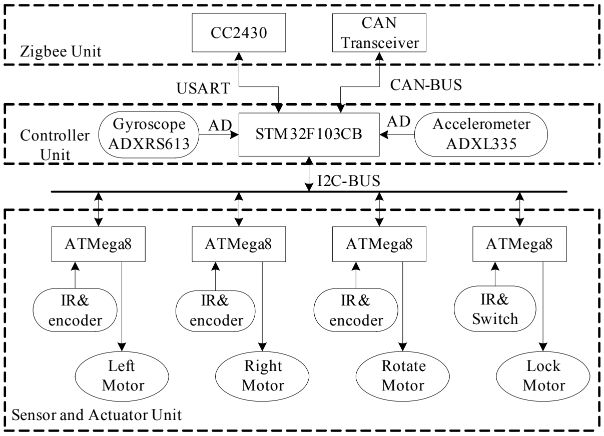

Fig.6.The electrical system of the Sambot

C. The communication unit

Sambot's communication is divided into two phases: ZigBee wireless communication in the dispersed state and CAN bus communication in the connection communication state. Zigbee communication uses TI's CC2430 chip with C51 microcontroller core for the realization of the underlying layer protocol stack and upper layer application, and CC2430 connect with main-control chip by serial interface. CAN bus communication uses VP230 as CAN transceiver to connect with the CAN interface in the main-control chip. When the robots get to connect, they also complete electrical connection by CAN bus. So the connected-robots can obtain the control information or other robots' state, and make corresponding actions.

As shown in Fig. 7, the robotic structure composed of multiple Sambots can have global communication through ZigBee modules. In it, each robot carries one CC2430 as a node, and the host PC is connected a CC2430 as coordinator. Together they form a mesh. Under this mesh structure, all the nodes (including the coordinator) can have communication between them. Each robot can not only transmit overall tasks and execute actions, i.e. have overall control, but collect information from other robots through the mesh, make autonomous decisions and realize distributed control.

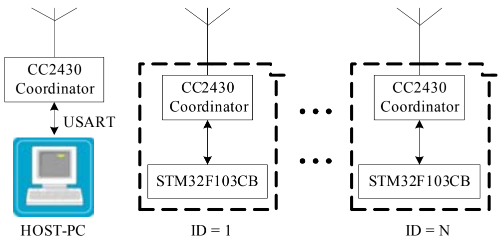

Fig.7. The ZigBee communication of multiple Sambots

V. SELF-ASSEMBLY AND CONFIGURATION ANALYSIS

A. *Self-Assembly*

The autonomous docking between two Sambots is the basis for realizing the self-assembly of multiple Sambots.

The autonomous docking between Sambots is divided into four phases, namely finding, guiding (navigating), docking and locking. At the beginning of docking, one Sambot (called the active Sambot), through the detecting infrared sensors detects the existence of another Sambot(called the passive Sambot). When it detects the passive Sambot, the docking infrared sensor at the active docking surface can receive the signal sent by the approaching infrared sensor at the passive docking surface of the passive Sambot; and then, guided by two pairs of docking infrared sensors, the active Sambot approaches the passive Sambot. When it approaches to a certain distance, the mechanical docking touch switch on the docking surface of the active Sambot is pressed down, triggers the active docking hooks to lock the docking grooves of the passive Sambot, hence the docking with the passive Sambot is realized.

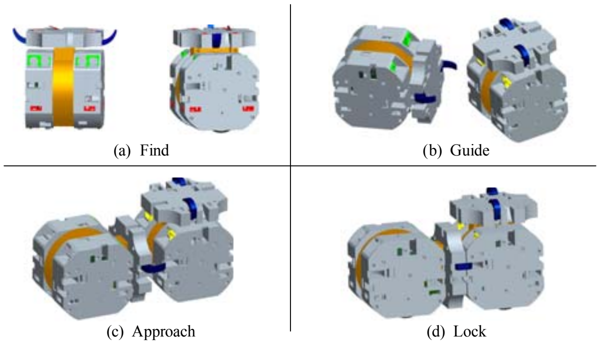
(a) Find (b) Guide (c) Approach (d) Lock

Fig. 8 Autonomous docking of two Sambots

B. *Configuration Analysis*

Multiple Sambots can compose a robotic structure through self-assembly. According to the design requirements, we build the Sambot modules using 3D software and assemble some Sambot module into several configurations. It can test the possibility of connection between modules, whether there are collision and interference or not, which prepares the good foundation for configuration construction under the experimental conditions. In accordance with distribution relationship between robot joints, we divide the configurations into linear configuration and multiped configuration.

Fig.9(a) shows a snake configuration in linear configuration, which is composed of six Sambots in series. The robots can make locomotion as a caterpillar through the rotation of rotary joints. Fig.9(b) shows the track configuration, which is more similar to the snake configuration, a total of 10 modules. The robots can make locomotion as a track through the rotation of rotary joints. Linear configuration is easy in morphology, and communication control is not complicated.

Fig.9(c) shows a four-legged configuration composed of 15 modules, which resembles a four-legged mammal. Three modules constitute “the backbone” and each leg is composed of three modules. Robot achieves walking through the rotation of the leg joints, and foot joints enable the contact between robot and ground as plane contact, which can enhance the stability. Fig. 9 (d) ~ (h) show the other configurations of a different number of modules, which can realize different locomotion patterns.

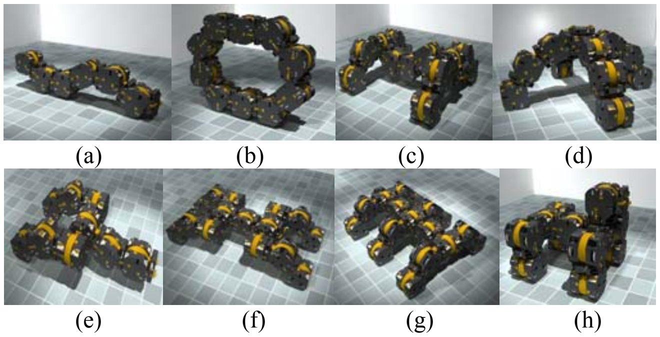
(a) (b) (c) (d) (e) (f) (g) (h)

Fig.9. The configuration of robotc structure assembled by multiple Sambot

VI. EXPERIMENTS

A. *The autonomous docking experiment*

The emphasis of this experiment is to test and verify the navigation function of the infrared sensor and the docking function of the active docking hooks. The experiment adopts the simple docking tactics. As shown in Fig. 10, an active Sambot rotates on the original position (a-b), and, according to the information from the detecting infrared sensor, searches goal Sambot (as Goal) in the proximity to be docked, then, at the position 15cm from the right side of the active Sambot, puts in Goal(c). According to the information from the infrared sensor, the active Sambot soon detects the new Goal (d), and approaches the goal (e) guided by the docking infrared sensor. When the active Sambot contacts the Goal (f), the mechanical touch switch on the active docking surface of the active Sambot is pressed down, the active Sambot to start lock the Goal tightly(g), the drive motor of the active hooks stop (h), relying on the worm gear and worm to lock the Goal tightly, thus finishing reliable autonomous docking.

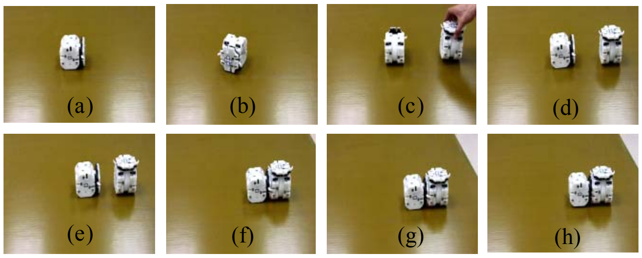

Fig.10 The autonomous docking experiment of two Sambot robots

B. *The reconfigurable experiment*

The experiment mainly verifies the reconfigurable function of the robotic structure composed of multiple Sambots by self-assembly. Thus the robotic structure relies mainly on the rotating mechanism on each Sambot active docking surface around the main body of Sambot to achieve the movement and reconfiguration. And the rotating mechanism needs enough torque to carry the other modules in the process of self-reconfiguration

As shown in Fig.11, the experiment establish a linear robot composed of 5 Sambot robots to lift one module and two modules, indicating that the Sambot has enough abilities of locomotion and reconfiguration.

This ability of the reconfiguration through coordinated transport between the modules provides Sambot with a new function, for example, a line configuration composed of 6 Sambots can form a closed track configuration through coordinated transport between the modules and roll along.

Fig.11 The configuration experiment of 5 Sambot

C. *Caterpillar locomotion experiment*

A whole locomotion experiment of robotic structure was done on a caterpillar configuration composed of 5 Sambots. The rotating range of each of the modules was 30°, delay was 300mm. In 9 seconds, the robot moved forward about the distance of 3.4 modules, about 280mm, so the actual moving speed of the robot was calculated as 30mm/s.

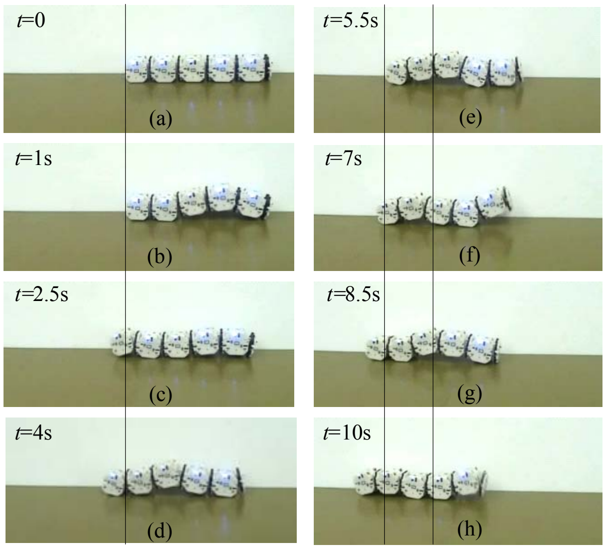

Fig. 12 The caterpillar locomotion of robotic sturcture assembled by 5 sambot

VII. CONCLUSIONS AND FUTURE WORK

This paper has put forward a novel self-assembled modular robot, Sambot, which is an autonomous mobile for both functions of self-assembly and self-reconfiguration. The paper introduced the mechanical design, electric design of the Sambot, and successfully conducted the autonomous docking reconfiguration and locomotion experiments of Sambots. All of this research has laid down a basis for further building robotic structure systems whose configurations and functions can evolve, and at the same time, has provided a research platform for the study of crossed mixing of swarm robots, self-reconfigurable robots and self-assembly robots.

Future research work mainly covers the following aspects: the first is to continue control algorithm and experiment of the self-assembly of multiple Sambots. The Second is to study the locomotion control of the robotic structure composed of multiple Sambots, and we hope, on the basis of the existing standard gait control table, to adopt a self-adaptive locomotion control used for Arbitrary reconfiguration, such as the CPG control, so as to improve the locomotion performance of the robotic structure. And finally, according to work missions and the varying environment, we intend to study the dynamic coupling of the control system and the structural configuration with the outside environment, and to build up a robotic platform whose configuration and function can both evolve.

REFERENCES

[1] G. M. Whitesides and B.Grzybowski, “Self-Assembly at all scales,” *Science*, vol. 295, no. 5564, pp. 2418-2421, Mar. 2002.

[2] R. Groß and M. Dorigo, “Self-Assembly at the Macroscopic Scale”, Proceedings of the IEEE. Vol 96(9), 1490 -1508, 2008.

[3] M. Yim, W. -M. Shen, B. Salemi, D. Rus, M. Moll, H. Lipson, E. Klavins, and G. S. Chirikjian, “Modular self-reconfigurable robot systems,” IEEE Robot. Autom. Mag., vol. 14, no. 1, pp. 43–52, 2007.

[4] A. Kamimura, H. Kurokawa, E. Yoshida, S. Murata, K. Tomita, and S. Kokaji, “Automatic locomotion design and experiments for a modular robotic system”, IEEE/ASME Trans. Mechatron., vol. 10, no. 3, pp. 314–325, 2005.

[5] Wei-Min Shen et al, “multifunctional behaviors of reconfigurable superbot robots”, Intelligent Robots and Systems, 2007. IROS 2007. IEEE/RSJ International Conference on Oct. 29 2007-Nov. 2 2007 Page(s):2548 – 2548, 2007

[6] R. Groß, M. Bonani, F. Mondada, M. Dorigo. “Autonomous Self-assembly in Swarm-Bots”, IEEE Transactions on Robotics, vol. 22, No. 6, p. 1115-1130, 2006.

[7] M. Yim, Y. Zhang, and D. Duff, “Modular robots,” IEEE Spectrum, vol. 39, no. 2, pp. 30–34, 2002.

[8] T. Fukuda and S. Nakagawa, “Method of autonomous approach, docking and detaching between cells for dynamically reconfigurable robotic system cebot,” JSME Int. J., vol. 33, no. 2, pp. 263–268, 1990.

[9] S. Hirose, R. Damoto, and A. Kawakami, “Study of super-mechano-colony (concept and basic experimental setup)”. In Proc. of the 2000 IEEE/RSJ Int. Conf. on Intelligent Robots and Systems, Vol3:1664–1669, 2000.

[10] H. B. Brown, Jr., J. M. V. Weghe, C. A. Bererton, and P. K. Khosla, “Millibot trains for enhanced mobility,” IEEE/ASME Trans. Mechatron., vol. 7, no. 4, pp. 452–461, Jul. 2002.

[11] M. Yim, D. G. Duff, and K. D. Roufas, “PolyBot: A modular reconfigurable robot,” *in Proc. IEEE Int. Conf. Robotics Automation*, vol. 1, pp. 514–520. Apr. 2000.

[12] M. Rubenstein, K. Payne, P. Will, and W. Shen, “Docking among independent and autonomous CONRO self-reconfigurable robots,” in *Proc.2004 IEEE Int. Conf. Robotics Automation*, vol. 3. New York:IEEE, pp. 2877–2882, Apr. 2004.

[13] C. Anderson, G. Theraulaz, J. Deneubourg, “Self-assemblages in insect societies,” *Insectes Sociaux* [Insectes Soc.]. Vol. 49, no. 2, pp. 99-110. 2002.

[14] R. Pfeifer, et al, “Self-organization, embodiment, and biologically inspired robotics, ” *Science*, vol. 318, no.5853, pp. 1088-1093, Nov. 2007.