Swarm Robots: From Self-assembly to Locomotion

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Inspired by the swarm behaviours of social insects, research into the self-assembly of swarm robots has become an attractive issue in the robotic community. Unfortunately, there are very few platforms for self-assembly and locomotion in the field of swarm robotics. The Sambot is a novel self-assembling modular robot that shares characteristics with swarm robots and self-reconfigurable robots. Each Sambot can move autonomously and connect with the other. This paper discusses the concept of combining self-assembly and locomotion for swarm robots. Distributed control algorithms for self-assembly and locomotion are proposed. Using five physical Sambots, experiments were carried out on autonomous docking, self-assembly and locomotion. Our control algorithm for self-assembly can also be used to realize the autonomous construction and self-repair of robotic structures consisting of a large number of Sambots.

Keywords: swarm robotics; self-assembly; autonomous docking; locomotion; distributed control

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1. INTRODUCTION

In insect societies, a number of very striking collective structures are formed by self-assembly. For instance, army ants may form a living bridge across a gap [1]. Inspired by the swarm behaviours of social insects, research into the self-assembly control of the swarm robot has become an attractive issue in the robotic community. Swarm robotics is the study of how a large number of robots of a relatively simple physical structure can be designed so that a desired form of collective behaviour emerges from the local interactions among the robots and between the robots and the environment [2]. Self-assembly is a process by which pre-existing components autonomously organize into patterns or structures without human intervention. They involve components from the molecular to the planetary scale and many different kinds of interactions [3].

In the field of robotics, self-assembly provides a very practical pattern of behaviour for the collaboration of swarm robots [4]. A group of modular units, or individual robots with identical functions, connect with each other in such a way as to form a robotic structure with stronger locomotion, sharper perception and better working ability than the individual modular units or individual robots. Therefore, the ability of these robots to self-assemble in a swarm makes them particularly useful for applications in unstructured, remote and hazardous environments such as deep sea and space exploration, urban rescue efforts and battlefields. Self-assembling swarm robots may provide important ways of designing and manufacturing robots with practical functions, and hence provide a basis for designing new robotics whose functions and morphologies can both evolve [5].

Thus far, most research work on swarm robotics has focused on the collaboration (e.g. formation and transportation through collaboration) and self-organized control of swarm robots. There are very few platforms that have the function of self-assembly. Furthermore, the robotic structures consisting of multiple individual robots do not have the function of wave-like locomotion [4].

In this paper, we discuss the concept combining self-assembly and locomotion for swarm robots, and propose the distributed control algorithms of self-assembly and locomotion. On the basis of on our self-developed novel self-assembling modular swarm robot (Sambot) [6], experiments were carried out on the autonomous docking, self-assembly and locomotion of multiple Sambots. The Sambot is a swarm robotic system that shares the characteristics of the swarm robot and the self-reconfigurable robot; that is to say, each Sambot is a completely autonomous
mobile robot, similar to the individual robot in swarm robotics. Through self-assembly, multiple Sambots can form a robotic structure with abilities of self-reconfiguration and locomotion similar to those of the self-reconfigurable robot.

This paper is organized as follows. In Section 2, related works on swarm robotics and self-assembling robots are discussed. In Section 3, the Sambot platform is introduced. In Section 4, the control model and controller of self-assembly are proposed, and the configuration analysis and locomotion control of a robotic structure consisting of multiple Sambots are discussed. In Section 5, experiments on autonomous docking, self-assembly and locomotion are conducted. In Section 6, we discuss the results of the experiments and control algorithms. Finally, the conclusions of the paper as well as the prospects for future research work are discussed.

2. RELATED WORK

Swarm robotics is usually referred to as a multi-robot system consisting of a great number of simple robots with identical functions, which imitates the group behaviours of species in nature, such as swarms of ants, schools of fish and flocks of birds, and realizes interaction and collaboration control among the individual robots, and between the individual robots and the surrounding environment [2]. Earlier research work includes the SWARM system [7], which is a distributed system composed of a great number of autonomous robots, which is characterized by low-intelligence robot modules.

With regard to research for existing platforms of swarm robots, the size of most of the robots is from dozens of millimetres to a hundred millimetres, and the robots have the abilities of autonomous motion and perception, such as Alice [8], e-Puck [9], Jasmine [10] and Kobot [11]. On research on the control model for swarm robotics, Li and Chen designed a general mathematical model for swarm robotics [12] and a formation navigation algorithm for multiple mobile robots [13]. Comparatively less research has been done on the self-assembly of swarm robots. The Swarm-bot is one of the few such platforms [14]. Swarm-bot is a homogeneous swarm robotic system composed of many autonomous robots, each of which is called an s-bot. The s-bot works with the gripper to clutch the connecting rings around another robot to realize the self-assembly of multiple s-bots. However, the Swarm-bot does not have the locomotion ability of the chain-typed self-reconfigurable robot system.

At present, research on the self-assembly of robots has mainly focused on modular robots and multiple mobile robots. In existing modular robot systems with self-assembly, the basic modules usually do not move on their own or their ability at autonomous mobility is very limited. The self-assembly is carried out by the robotic structure composed of two or more basic modules, such as PolyBot [15], CONRO [16], CKbot [17], ATRON [18] and M-TRAN [19]. In multiple mobile robots with self-assembly, each individual robot, such as CEBOT [20], Gunryu [21], SMC [22], Millibot [23] and others, has the functions of autonomous motion and docking. Because of the limitations of structural design and control, these platforms can only demonstrate self-assembly between a few individual robots.

3. ROBOT PLATFORM

3.1. Outline of the Sambot

The Sambot is an autonomously mobile and self-assembling robot, and includes the power supply, microprocessors, sensors, drives and wireless communication module. The overall size of the Sambot is \(80 \times 80 \times 102\) mm and the weight is 400 g.

As shown in Fig. 1, in terms of structure the Sambot is divided into an active docking interface and main body. On the active docking interface, there is a pair of active docking hooks, which can dock with the four docking grooves (in the front, back, left and right passive docking interface) on the main body of other Sambots. The mechanical design of the docking hooks and docking grooves allows two Sambots to realize autonomous docking and locking within some limits of misalignment. The mechanical contact switch and docking infrared sensor on the active docking interface are used to guide and judge whether the two Sambots are in the state of docking, and provide information for the active docking hooks to tightly lock the docking grooves on the other Sambot. On the upper side of the front and back of the main body are installed two pairs each of detecting infrared sensors, which are used to detect obstacles in front of the robot; on the lower side of the front, back, left and right interface of the main body are two pairs each of approaching infrared sensors, which, by reacting with the docking infrared sensors on the active docking interface of the other Sambots, monitor the relative positions of the two Sambots and provide navigation information during the autonomous docking.

The Sambot’s control system consists of an STM32 microprocessor and four ATmega8 microcontrollers. The STM32 has been used to localize the robot’s navigation...
and also for decision-making tasks, whereas the ATMega8 microcontrollers have been used for motor control and information collection by the sensors. There are two types of communication systems in the Sambot: the ZigBee wireless communication in the dispersed state and the CAN bus communication in the connection state.

3.2. Docking mechanism

Sambot selects a worm-driven docking hook mechanism, which realizes connection and disconnection through locking by a pair of active docking hooks with the docking grooves of another Sambot.

The docking grooves are arranged asymmetrically to allow synchronized docking of the front, back, left and right interfaces without interference. As shown in Fig. 2, Sambot A and Sambot B are docked by hook 1 (the lines in boldface show the contact sides of Sambot A and Sambot B). Sambot C now needs to be docked with Sambot B by hook 2. To avoid interference, when hook 2 rotates into the grooves of Sambot B, there are also open grooves on the active docking interface of Sambot A. In this way, the synchronized docking of multiple Sambots with the four interfaces of front, back, left and right is realized without interference.

3.3. Self-assembly and locomotion

After multiple Sambots form a robotic structure with a certain configuration (such as the snake robot shown in Fig. 3) through self-assembly, the robotic structure can produce wave-like locomotion. In addition, the robotic structure can change its configuration and realize self-reconfiguration in adapting to various missions and environments. Since each Sambot is an autonomous mobile robot, the robotic structure is able to realize reconfiguration not by relying on the relative transport between the modules, but through disconnecting and re-docking between the Sambots.

Fig. 3 shows the robotic structure reconfigures from a snake-like into a quadruped configuration. Through the disconnect and autonomous move and re-docking between the Sambots, the new configuration can be quickly built up.

4. CONTROL ALGORITHMS OF SELF-ASSEMBLY AND LOCOMOTION

During the self-assembly process, the Sambot only has the ability to engage in limited infrared sensing and local communication. Therefore, the following constraints apply:

(i) None of the robots have global coordinate information, and none are capable of implementing global navigation control.

(ii) The robots only have local sensing ability. Each robot detects targets using its detecting infrared sensors and navigates using its approaching infrared sensors.

(iii) Each robot only has local communicating ability (although Sambot has ZigBee global communication, we do not use it in the self-assembly process).

4.1. Control model

In order to ensure smoothness during motion, two spring flakes are installed on the inside of the two driving wheels of the Sambot. This causes the spring flakes to keep contact with the ground when the Sambot is autonomously moving, thus achieving smoothness during motion. In addition, the frictional force with the ground is kept at a minimum. A kinematic model of the Sambot is shown in Fig. 4. In the kinematic model, we ignored the effect of the spring flakes.

The position and attitude, and velocity and angular velocity of a Sambot can be expressed by \((x, y, \varphi, v, \omega)\). The kinematic equation of the Sambot is shown as follows:

\[
\begin{bmatrix}
  x \\
  y \\
  \varphi
\end{bmatrix}
= \begin{bmatrix}
  \cos \varphi & 0 & 0 \\
  \sin \varphi & 0 & 1 \\
  0 & 1 & 0
\end{bmatrix}
\begin{bmatrix}
  v \\
  \omega
\end{bmatrix}
\]  

\[
\begin{equation}
\begin{aligned}
  v &= \frac{r}{2}(\omega_1 + \omega_2),
\end{aligned}
\end{equation}
\]
According to the kinematic model, the Sambot has established

\[ \omega = \frac{r}{2R} (\omega_l - \omega_r), \]

where \( 2R \) is the distance between the two wheels, \( \omega_l \) is the angular velocity of the left wheel, \( \omega_r \) is the angular velocity of the right wheel, \( v \) is the moving speed of the robot and \( \omega \) is the angular velocity of the robot.

When \( v > 0 \) and \( \omega = 0 \), the robot makes a linear motion; if \( v > 0 \) and \( \omega > 0 \), the robot makes a circular motion; if \( v = 0 \) and \( \omega > 0 \), the robot makes a self-rotating motion. By controlling the moving speed and the angular velocity, the position and orientation of the Sambot can be controlled.

Sambot adopts the behaviour-based control method, that is, the controller is composed of a series of behaviours, and each behaviour is used to realize a specific function. In addition, each behaviour is the combination of a series of motor schemes. According to the kinematic model, the Sambot has established the following basic motor schemes:

(i) Rotate (\( \omega, \Phi \)): rotates at angular velocity \( \omega \), self-rotate angle \( \Phi \), \( \Phi \in (-180^\circ, 180^\circ) \).

(ii) SetMoveSpeed (\( V_l, V_r \)): sets the velocity of the left and right wheels of the Sambot, \( -4000 \leq (V_l, V_r) \leq 4000 \).

(iii) Forwards (\( v, L \)): with velocity \( v \) moves forwards for a distance \( L (L \geq 0) \).

(iv) Backwards (\( v, L \)): with velocity \( v \) moves backwards for a distance \( L (L \geq 0) \).

(v) ARC (\( \omega, R, \psi \)): at angular velocity \( \omega \), with the current point as the starting point, with \( R \) as the radius, the moving angle as the circular arc of \( \psi \), \( \psi \in (-180^\circ, 180^\circ) \).

(vi) DockBoard_Rotate (\( \omega_m, \Phi \)): the active docking interface rotates at an angular velocity \( \omega_m \), rotates at an angle \( \Phi \), \( \Phi \in (-180^\circ, 180^\circ) \). This action can be used for the whole locomotion control of the robotic structure after self-assembly.

(vii) Lock (): the docking hook locks, executes the locking of two Sambots.

(viii) Unlock (): the docking hook opens, executes the separation of two Sambots.

The Sambot mainly relies on its infrared sensors to detect the surrounding environment, and decides on its behaviours. For convenient modelling of the control system, the following definition is given of the Sambot’s sensors:

(i) Four pairs of detecting infrared sensors: two pairs each in the upper side of the front and back interface of the Sambot are used to detect other Sambots or obstacles. Its range is 0–160 mm.

(ii) Eight pairs of approaching infrared sensors: two pairs each in the lower side of the front, back, left and right interface of the Sambot are used to provide navigating information for the self-assembly process. Its range is 0–150 mm.

(iii) Four pairs of docking infrared sensors: two pairs each in the lower and upper side of the active docking interface are used for guiding during the autonomous docking process. Its range is 0–150 mm.

(iv) Mechanical contact switch: if the mechanical contact switch is pressed down, the docking hooks can lock the docking grooves of other Sambots.

(v) Electronic compass sensor: indicates the orientation of the Sambot, \( \beta \in (0 - 360^\circ) \).

4.2. Self-assembly controller

We suppose that the experiments on autonomous docking and self-assembly are implemented in a bounded experiment platform. A passive docking Sambot is used as the target robot called Goal_SA, and all active docking Sambots are used as the active robot called Active_SA. The self-assembly process is started by Goal_SA.

As shown in Fig. 5, Goal_SA is located in the centre of the experiment platform. Throughout the self-assembly process, Goal_SA’s position and orientation remain unchanged. In accordance with the self-assembly task, Goal_SA only switches on its approaching infrared sensors, which are located on lower side of the passive docking interface (called Docking_Direction), while waiting for Active_SA to come with its own docking. In Fig. 5, the Docking_Direction is the left interface of Goal_SA.

In the paper, we define the self-assembly process as Goal_SA not being in sight of the infrared detecting sensors of Active_SA. The Active_SA needs to wander and to search for Goal_SA using its detecting infrared sensors, then navigate around Goal_SA to find the Docking_Direction. In order to achieve self-assembly control, the Sambot should have three basic behaviours: Search_goal, Navigation and Autonomous docking.

4.2.1. Search_goal behaviour

This behaviour is to switch on the front detecting infrared sensors, and wander randomly. The four edges of the experiment platform are 40 mm high (higher than the approaching infrared sensor and lower than the detecting infrared sensor). When
Algorithm 1 Search_goal behaviour.

1. While Goal_SA is not found, do
2. Initialization Open front detecting and approaching IR
3. Forward until detecting a edge
4. If Active_SA approaches an edge
5. Then
6. Turn around to be parallel with the edge
7. Move along the edge to one corner of the platform
8. Turn around to the centre of the platform
9. Move to the centre of the platform
10. Turn a circle to search for Goal_SA
11. If Goal_SA cannot be found, break
12. Otherwise Active_SA must approach a corner
13. Then
14. Turn around to the centre of the platform
15. Move to the centre of the platform
16. Turn a circle to search for Goal_SA
17. If Goal_SA cannot be found, break
18. End while

Active_SA wanders to the edge of the experiment platform, its approaching infrared sensors give a signal, and the robot goes backwards. When its front detecting infrared sensors has input information, which means that Goal_SA is found, then Active_SA transits to navigating behaviour.

4.2.2. Navigation behaviour

In the navigation behaviour, through the limited perceptive ability of the infrared sensors of the Sambot itself, the Active_SA moves anticlockwise around Goal_SA, until it finds the Docking_Direction of Goal_SA. Active_SA first adjusts its orientation to align itself with Goal_SA (the orientation of the Goal is predetermined), then itself rotates and records the relative location angle $\alpha$ of itself with Goal_SA. This is so that Active_SA can move forwards a short distance and then turn left, until its detecting infrared sensors detect Goal_SA. Active_SA then turns right at a slight angle, and continues to repeat this process. During this process of navigation, Active_SA always keeps its approaching infrared sensors facing Goal_SA switched on, and as soon as it receives the information, Goal_SA has arrives at the Docking_Direction of Goal_SA. The navigation behaviour then ends, and there is a transition to the Autonomous docking behaviour.

Algorithm 2 Navigation behaviour.

1. While Active_SA doesn’t detect Docking_Directions, do
2. If the left detecting IR sensor doesn’t detect Goal_SA
3. Then
4. Turn left to detect Goal_SA
5. Turn right by 30°
6. Forward 80 mm
7. Otherwise, the left detecting IR sensor detects Goal_SA
8. Turn right until the left detecting IR doesn’t detect Goal_SA
9. Turn right by 30°
10. Forward 80 mm
11. End while

4.2.3. Autonomous docking behaviour

The Active_SA is required to switch on the docking infrared sensors on the active docking interface and, according to the signal from the approaching infrared sensors of Goal_SA, adjusts its own position and approaches in the direction of Goal_SA, until the mechanical contact switch on the active docking interface is pressed down and the docking hooks on Active_SA can lock Goal_SA. Here, the electric touch points of both Active_SA and Goal_SA contact each other, and send a handshake to confirm the completion of the CAN Bus communication connection. Afterwards, Active_SA sends basic information about itself, such as ID, to Goal_SA. Active_SA confirms the connection with Goal_SA, and the docking is accomplished.

Algorithm 3 Autonomous docking behaviour.

1. while do
2. Adjust the location by moving in the current direction
3. to make sure both approaching IR sensors on the
4. left side detect the IR signal from Docking_Direction
5. Turn 90° towards Docking_Direction
6. Forward and adjust direction according two
7. approaching IR sensors on the front side
8. If succeeding in touch with Docking_Direction
9. then Lock ($\alpha$);
10. Otherwise transit to Search_goal behaviour
11. End while

4.3. Locomotion controller

The robotic structure composed of multiple Sambots has outstanding ability in locomotion. When multiple Sambots are connected, each Sambot is equal to a module of the robotic structure. The robotic structures formed by multiple Sambots are actually chain-type self-reconfigurable robots. As shown in...
Fig. 6, we have designed a number of locomotion configurations of the robotic structures.

Figure 6a shows a linear configuration, which can make locomotion like a caterpillar by rotating the joints of each module. Figure 6b shows the track configuration, which can move like a track by rhythmically rotating the joints of each module. Figure 6c–f shows the tripod configuration, cross quadruped configuration, parallel quadruped configuration and hexapod configuration, respectively.

As shown in Fig. 7, we take the locomotion of the caterpillar assembled with five Sambots as an example, with nodes S1, S2, S3, S4 and S5 as the five Sambots. Here, a gait control table is used to establish the gait control of the caterpillar configuration [24]. A sinusoidal wave propelling movement is used, the maximum oscillating amplitude is 30° and the anticlockwise rotation is positive.

According to the result of the locomotion analysis, the sinusoidal wave forward-moving gait of the caterpillar is shown in Table 1.

The robotic structure assembled with multiple Sambots uses the distributed CAN Bus control. There is one main control robot (S1), and the rest of the Sambots are subordinate robots (S2–S5). The gait control table is saved by the main control node S1, and S1 sends the gait and delay time to S2–S5 successively. In the caterpillar movement, the distributed gait control algorithm of S1 is as shown below:

Algorithm 4 Distributed caterpillar gait control.

<table>
<thead>
<tr>
<th>Node’s movement</th>
<th>Period no.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>S1</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>+30°</td>
</tr>
<tr>
<td>2</td>
<td>+30°</td>
</tr>
<tr>
<td>3</td>
<td>-30°</td>
</tr>
<tr>
<td>4</td>
<td>-30°</td>
</tr>
<tr>
<td>5</td>
<td>+30°</td>
</tr>
</tbody>
</table>

5. EXPERIMENTS

5.1. Autonomous docking experiment

The emphasis in this experiment is to test and verify the navigation function of the infrared sensors and the docking function of the active docking hooks. As shown in Fig. 8, an Active_SA rotates on the original position (Fig. 8a and b) and, according to the information from the detecting infrared sensor, searches for Goal_SA in the proximity to be docked. Then, at a position 15 cm from the right side of Active_SA,
puts in Goal_SA (Fig. 8c). According to the information from the detecting infrared sensor, Active_SA soon detects Goal_SA (Fig. 8d) and approaches Goal_SA (Fig. 8e) guided by the docking infrared sensor. When Active_SA contacts Goal_SA (Fig. 8f), the mechanical contact switch on the active docking interface of Active_SA is pressed down, Active_SA starts to lock Goal_SA tightly (Fig. 8g) and the drive motor of the active hooks stop (Fig. 8h), relying on the worm gear and worm to lock Goal_SA tightly, thus completing reliable autonomous docking. We performed this experiment 10 times. Active_SA succeeded in docking with the Goal_SA nine times, and failed once as a result of an excessive initial error. The time that elapses from when Active_SA finds Goal_SA to succeeding in docking with it is generally ~16 s.

5.2. Self-assembly experiment

The self-assembly experiments are conducted on an experiment platform of 600 × 600 mm. In the initial state of self-assembly, Goal_SA is located in the centre of the experiment platform, and all of the Active_SAs are located in the four corners of the experiment platform. We tried to make a self-assembly experiment to construct a cross quadruped configuration using five Sambots.

The self-assembly between the Sambots is as shown in Fig. 9. First, Active_SA switches on the detecting infrared sensors, wanders around and, when it comes to the edge of the experiment platform, turns a random angle and continues to move forwards, until the detecting infrared sensors have information inputted to them and mean to find Goal_SA. Now, the state of Active_SA transits to navigation. During navigation, Active_SA switches on the approaching infrared sensors on the left side and, according to the information from the detecting infrared sensors and the left approaching infrared sensors, moves anticlockwise around Goal_SA, until its approaching infrared sensors has information inputted to it, showing that it has found the Docking_Direction of Goal_SA. Then Active_SA transits to the autonomous docking behaviour. Its active docking interface rotates 90°, ensuring that the docking infrared sensors on the right and left have information inputted at the same time. Active_SA then moves forwards, until the mechanical contact switch is pressed down, and the docking hooks lock in tightly, thus finishing the self-assembly. This process continues until other Goal_SAs have in turn completed the task of self-assembly.

Including putting Docking_SA on the platform manually, the whole process of self-assembly is completed within 290 s. We record the time that each Active_SA spent on Search_goal, Navigation and Autonomous Docking, as shown in Table 2.

From Table 2, we can see that the autonomous docking time is the least, and for different Active_SAs, the autonomous docking times are approximately equal. The search_goal time is random, and because the experiment platform is 600 × 600 mm, each Active_SA can find Goal_SA quickly. The navigation time among different Active_SAs differs because of the different locations of Connect_Direction.

5.3. The locomotion experiment

A locomotion experiment of a robotic structure consisting of five Sambots was conducted. The rotating range of each of the modules was 30° and the delay was 300 ms. As shown in Fig. 10, in 9 s, the robot moved forwards at a distance of ~3.4 modules, or ~280 mm, so the actual moving speed of the robot was calculated as 30 mm/s. During the caterpillar locomotion, each
Sambot in the robotic structure is affected by a different ground force, and so the waveform is not a strict sinusoidal.

As shown in Table 3, the locomotion distance of the robotic structure is measured to analyse the kinematic characteristics and accuracy of its locomotion. Five experiments are performed and the given control parameters in each experiment are the same. From these statistical data, it is obvious that the locomotion is stable and accuracy is enough in both the forward and lateral directions.

### 5.4. From self-assembly to locomotion

In this experiment, the self-assembly and locomotion are combined in the following way: (i) several Sambots firstly form a caterpillar-like robotic structure through self-assembly; (ii) a wave-like locomotion is then implemented.

This experiment is conducted on an experiment platform of 1000 × 1000 mm. In the initial state, Goal_SA is located in the centre of the experiment platform, and four Active_SAs are in the four corners of the experiment platform. For the caterpillar-like configuration, the Docking_Direction is the back interface of Goal_SA. The arrow indicates the Docking_Direction. The experiment process is shown in Fig. 11.

All of the Active_SAs perform the Search_goal behaviour simultaneously. At the fifth second, Active_SA no. 1 finds Goal_SA, and transits to Navigation behaviour. In the 23rd second, it finds the Docking_Direction of Goal_SA and then switches to autonomous docking behaviour. At the 34th second, Active_SA no. 1 completes docking with Goal_SA and switches on the approaching infrared sensors in its back interface as the new Docking_Direction. The process goes on until other Goal_SAs have completed the self-assembly task in turn. The self-assembly times for all Active_SAs are shown in Table 4. The whole self-assembly process is completed in 169 s. After self-assembly, the robotic structure starts to perform the task of locomotion. In the locomotion process, the control method is the same as in the above locomotion experiment.
TABLE 4. The time of self-assembly and locomotion.

<table>
<thead>
<tr>
<th>No.</th>
<th>Search_goal(s)</th>
<th>Navigation(s)</th>
<th>Autonomous docking(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5</td>
<td>18</td>
<td>11</td>
</tr>
<tr>
<td>2</td>
<td>31</td>
<td>98</td>
<td>12</td>
</tr>
<tr>
<td>3</td>
<td>34</td>
<td>31</td>
<td>11</td>
</tr>
<tr>
<td>4</td>
<td>111</td>
<td>46</td>
<td>12</td>
</tr>
</tbody>
</table>

6. DISCUSSIONS

The Sambot is a novel physical robotic platform that has integrated the characteristics of the swarm robot, the self-assembly robot and the self-reconfigurable robot. Recently, some researchers have begun to pay attention to the study of swarm robots with the abilities of both self-assembly and self-reconfiguration. Kernbach and coauthors have begun the research projects of SYMBRION and REPLICATOR [25]. The aim in these research projects is to combine the strength of the swarm robot and the reconfigurable robot, and adopt the ways of emulation and evolution computing to develop a new type of autonomous multiple robots. Each robot in this multiple robot system is an independent and autonomous mini-robot, but these mini-robots need to be assembled into one robotic structure in order to achieve greater ability. The SYMBRION explored the main principles of artificial evolution and embodied pervasive adaptation, whereas the REPLICATOR strongly focused on the cognitive capabilities of artificial organisms and their industrial applications. The first phase of the work was a basic experiment on docking guidance and self-organizing control based on the Jasmine robot [26]. So far, there has been no report of research on the prototype robotics of self-assembly and self-reconfiguration.

The structural design of the Sambot goes far in realizing the combination of the swarm robot and self-reconfigurable robot; i.e. on the one hand, it has the autonomous moving ability of the swarm robot, whereas on the other hand, its autonomous docking and locomotion abilities are as good as those of existing self-reconfigurable robots.

With regard to the self-assembling robot, most research work relies on high-performance sensors such as cameras and laser range finders to achieve the docking of two mobile robots. The Swarm-Bot platform [14], for example, relies on a combination of cameras and an LED ring to carry out positioning and navigating between two robots. The M-TRAN [19] achieves docking between modules using an additional camera module. In our experiments, the Sambot relies only on its limited infrared sensing ability to achieve the identification of other Sambots and obstacles. This characteristic of limited sensing and local communication keeps down the cost of the Sambot, making it suitable for mass production.

In addition, our self-assembly control algorithm is decentralized, in that the Active_SA only performs the task of a simple state machine controller without any information about the target configuration and global coordination. Therefore, this control algorithm can be directly extended to the implementation of more Sambots without any modification.

7. CONCLUSIONS AND FUTURE WORK

The swarm robots with self-assembly and locomotion achieve the unity between self-reconfigurable robots and self-assembly robots and swarm robotics, which greatly expands the application fields of swarm robotics and self-reconfigurable robots, and has very important practical value. In this paper, we propose a distributed self-assembly control algorithm and demonstrate the ability of self-assembly and locomotion of the Sambot. Furthermore, the experiment from self-assembly to locomotion has been conducted. The experimental results show our self-assembly algorithm can directly be extended to a large number of Sambots.

Future research work will be mainly focused on the following aspects: the first is to combine the parallel control algorithm of the self-assembly of multiple Sambots. The second is to make more sambots to further perform experiments on swarm robotics. The third is to study the CPG locomotion control of the robotic structure composed of multiple Sambots, so as to improve the locomotion performance.

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REFERENCES


