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REVIEW PAPER

Research on Reconfiguration Strategies for Self-reconfiguring Modular Robots: A Review

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Abstract

With the progress of science and technology, the traditional robot workplace is fixed, single-function, and inflexible, and may not work properly in some special places, while the modular robot with self-reconfiguration function is a robot that can adapt to new environments and can rely on new task settings, which has a series of universal modules and relies on mutual communication between modules and autonomous reorganization movements to cope with changes in the environment or tasks and recover from the state of destruction. This paper summarizes the representative international research results from the perspective of the hardware design of robots in two aspects based on the design characteristics of self-reconfiguring modular robots around the reconfiguration strategy planning method. At the same time, some existing problems and shortcomings are pointed out on this basis to provide ideas as well as perspectives for future research development.

Keywords Modular robots · Self-reconfiguration · Target configurations · Reconfiguration strategies · Configuration matching

1 Introduction

With the modernization of society and the continuous advancement of technology, more and more scenarios require the use of robots, which are highly efficient, safe, and reliable, and the application of robots can help humans to deal with various dangerous scenarios of work [1, 2]. To improve the environmental adaptability of robots, it is of great importance to design self-reconfiguring modular robots that can meet the needs of different tasks for the development of various industries [3–7].

Self-reconfiguring modular robots are practical, flexible, and suitable for workplaces in a variety of complex environments. Multiple cell modules can form a variety of configurations of robots, and the reconfigurability of the robot can be used in a variety of settings to accomplish different work goals. It is this reconfigurability that makes it highly adaptable to the environment and therefore has a wide range of applications in extreme environments for operations in extreme environments, disaster rescue, military fields, and planet exploration [8, 9]. Self-reconfiguring robots can be divided into homogeneous cell modules and non-homogeneous cell modules according to whether the modules are identical in function and configuration [10]: homogeneous systems are those in which the modules that make up the robot are identical in structure and function and the system can be extended with more modules to achieve more configurations as needed due to identical hardware and software, and they are also more self-healing than non-homogeneous systems when a module in the system fails; A non-homogeneous system is one in which there are multiple modules with different structures or functions that make up the robot, and each type of module plays different roles in robot reconfiguration, motion, and task execution, such as Mole-cube [11–14], and USS [15, 16]. The self-reconfiguration task of non-homogeneous systems becomes relatively difficult due to the large variety of modules and their varying functions. At present, relevant researchers have started the study of self-reconfiguring robots, but no systematic theory has been

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formed, especially in the aspect of conformation recognition, researchers have only analyzed the chain conformation, and the recognition of the ring-containing conformation has not been effectively solved.

For the self-reconfiguration modular robot summary analysis has tended to be perfect, Zhang Yan [17] from the modular self-reconfiguration robot three different connection structure of the physical principles and basic structure, the robot module reconstruction algorithm and the rapidity of the reconstruction process of the three aspects of technology, analysis and summary of its advantages and disadvantages as well as the current situation of the development; Ning Hao [18] on the development trend of the self-reconfiguration modular robots analytical study, but at present for the Although many scholars have proposed different reconfiguration strategies for self-reconfigurable modular robots, very few scholars have made a systematic summary and analysis of existing reconfiguration strategies. In this paper, we study the design concepts and design classifications of the reconfiguration strategies of homogeneous self-reconfigurable modular robots, and we summarize and introduce the existing reconfiguration strategies of self-reconfigurable modular robots from two aspects and analyze their advantages and disadvantages in terms of reconfiguration efficiency, applicability, speed, and development status. Comparisons are made in terms of reconfiguration efficiency, applicability, and energy consumption, which are visually illustrated through pictures and tables to provide some references for future research on the structural design of self-reconfigurable modular robots and their reconfiguration strategies.

2 Modular Robot Reconfiguration Design Concepts

In the past four to five decades, many new algorithms have emerged in the computer science community to solve various complex computational problems. Many researchers have been committed to using new algorithms to solve engineering applications in the field of robotics. At present, according to whether the modular robots can be self-transformable configuration, they are divided into self-reconfigurable modular robots and reconfigurable modular robots [19]. Since the 1990s, with the high interest of researchers in the study of self-reconfigurable modular robots, self-reconfigurable modular robots began to develop rapidly, and several experimental prototypes have been built to address the problems in the field of self-reconfigurable modular robots and the problems in the field of self-reconfigurable modular robots. A number of experimental prototypes have been built, some solutions have been proposed for the problems in the field of self-reconfigurable modular robots, and computer simulations of the self-reconfiguration process have been carried out. LIU, YIM et al.-based on the Poly bots system, a hierarchical and step-by-step conformation matching and reconfiguration planning has been proposed to complete the conversion of the serpentine to the quadrupedal conformation [8, 20]; HOU et al. combined with the DFS, utilized the graph theory, and carried out the deformation lines of chained self-reconfigurable robotic system Reconfiguration Theory Research KAMIMURA et al. carried out centralized hierarchical planning for overall and local reconfiguration for the hybrid module M-TRAN [21]. Su Shicheng and Fei Yanqiong described the lattice module M -Cube system using eigenvector matrices to establish connection and reconstruction rules [22, 23], but could not accurately express the system spatial position; Zhao Jie "for the chain module Ubot [24], using the association matrix for the topological expression of the system, realized two-level matching between configurations and hierarchical reconfiguration planning, but did not consider the reconstruction when the dynamics conditions of the reconfiguration. The research on self-reconfiguring modular robots has so far been conducted mainly in the perspective of configuration design and docking control, while there is still much room for progress in the direction of self-reconfiguration strategies. Currently, the research on self-reconfigurable robots mainly focuses on the following aspects: the design of self-reconfigurable robot unit modules, the study of reconfiguration algorithms, and the study of overall coordinated motion planning [25].

With the wide application of industrial robots, various kinds of work tasks put forward different requirements on the structure of robots, which prompts people to consider the modularization of industrial robots. Since the first self-reconfigurable robot CEBoT [26–28] was introduced, related scholars have studied it in terms of structural design, motion planning, and reconfiguration strategies. Many experimental prototypes have been developed, and some progress has been made in the aspects of reconfiguration algorithms, coordinated motion planning and other theoretical studies. The flexibility, robustness and scalability of self-reconfigurable robotic systems are outstanding, which greatly enriches the functions of robots, and thus they are more applied to the fields of disaster rescue, military reconnaissance, and aerospace exploration [29, 30], and reconfiguration strategy will become an important development direction of robotic systems [19, 31, 32]. Self-reconfigurable robots can be categorized into lattice, chain, and hybrid based on the connection relationship between modules, the motion form of modules, and the topology of modules [33–35]. The reconfiguration strategy mainly investigates the connection, disconnection position and timing between modules during the robot configuration transformation [36, 37]. The reconfiguration strategy of the modules determines the reconfiguration capability of the robot, but the application of the reconfiguration strategy is constrained by the structure and function of the modules. Thus, the current reconfiguration strategies are classified into lattice-constraint-based reconfiguration strategies and chain-type reconfiguration strategies based on the characteristics of the modular robot ontology design. The self-reconfiguration of lattice-based modular robots is constrained by the grid, and the space where the system is located needs to be divided into grids during the reconfiguration process, i.e., the space occupied by each module is a grid, and thus the exact paths and motions of the modules that are moved between the grid positions need to be clarified before the reconfiguration [33, 38]. The unit modules of chained modular robots are free from the constraints of the grid in the reconfiguration motion and connection, and can reach any position within the range of their workspace through planning, and reconfiguration deformation can be realized through the docking and disconnecting between modules. This makes the reconfiguration motion no longer limited to the movement of a single module but generates the movement of an entire branched chain, thus increasing the complexity of the reconfiguration strategy [39]. The main feature of modular self-reconfiguring robots that distinguishes them from traditional robots lies in the ability to change the relative positions and connections between internal modules through inter-module relative movement according to the environment and task needs to realize the migration of the overall center of mass and the reorganization of the system configuration, which is known as the reconfiguration of modular self-reconfiguring robots, and includes both reconfiguration motion and reconfiguration deformation [40]. The process of self-reconfiguration of a modular robot is the transformation from an initial configuration to a target configuration (for the self-reconfiguration process without an initial configuration, the dispersed cells or tissues can be regarded as the initial configuration), which can be module-to-module, module-to-robot, or robot-to-robot, which enables modular robots to have superior functionality and a wider range of application areas [40, 41]. Its self-reconfiguration can be divided into two steps: self-deconstruction and self-assembly. The self-deconstruction process is to deconstruct the initial target and break it into independent organizations or several small configurations. The self-assembly process is to use simple assembly rules to gather a set of existing but disordered components into a well-organized and well-constructed structure. The self-assembly process is to solve for the common topological parts of the two configurations, after comparing the subchains to find out the common topological parts using the textual comparison method. Finally, the self-assembly order is determined by solving the self-assembly order to determine the order of autonomous linkage pulling of the modules to carry out the assembly of the conformations from the common topological part to the target conformations [3, 42, 43].

The reconfiguration strategy of a module determines the reconfiguration capability of the robot, but the application of the reconfiguration strategy is constrained by the structure and function of the module. As a result, the current reconfiguration strategies are classified into grid constraint-based reconfiguration strategies and chained reconfiguration strategies based on the characteristics of modular robot ontology design.

3 Reconfiguration Strategy Based on Modular Robot Ontology Design Classification

In the following, the existing refactoring strategies are classified into two categories as shown in Fig. 1.

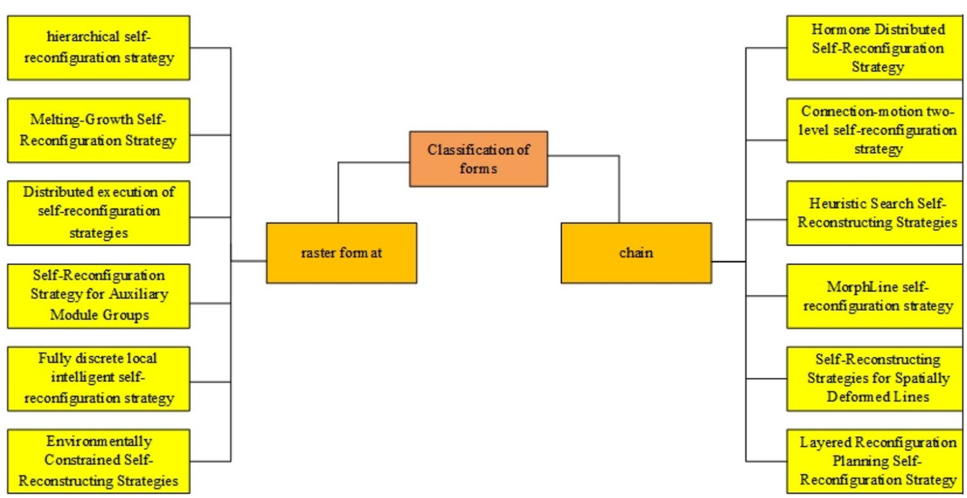


Fig. 1 Reconstructing the strategy categorization framework

3.1 Self-Reconfiguration Strategy for Raster Format

The self-reconfiguration strategy based on grid constraints divides the space in which the system is located into a grid in the self-reconfiguration process, and the space occupied by each module is a grid, and in the process of self-reconfiguration planning, it is necessary to indicate the exact movement path and the movement of the module from one grid position to another [44]. Thus, for this type of reconfiguration, a set of motion sequences includes: the target motion module is separated from the robot body, moved or transported along the surface of the robot body, and then reconnected to the robot body at a new location.

Initially, planning algorithms were focused on centralized control. Centralized planning methods usually build a tree of all possible configurations using metrics and heuristic-guided search. Chirikjian, G. [45] bounded the upper and lower bounds on the minimum number of motion steps required to change from the initial configuration to the final specified configuration. Ineffective motion planning strategies can be improved by such developed bounds. Here three configuration metrics are defined to measure the distance between two configurations and a simulated annealing algorithm is applied to drive the reconfiguration process with the reconfiguration metric as a cost function.

3.1.1 Hierarchical Self-Reconfiguration Planning Algorithm Self-Reconfiguration Strategy

Chiang proposed a self-reconfiguration algorithm [46] based on the recursive leveling of robot configurations to improve the overall performance reconfiguration with a defined number of intermediate configurations. This algorithm is to divide the self-reconfiguration planning task into multiple steps or levels to complete. In the Hexagonal [47] system, modules can scroll along a grid composed of other modules. Through contact sensors, a module can sense the presence of all the modules around it that are connected to it and also to be informed of its orientation (orientation of each edge) [45, 48]. The self-reconfiguration algorithm is executed in two phases. The first stage is a centralized planning phase that determines the feasibility of the reconfiguration task and the final coordinates of all the modules in the system after reconfiguration. This is achieved by creating a directed graph towards and through the target module in the target conformal region. Phase 2: Planning the specific implementation of the process of moving the target module from its current position to the target position. This second stage is accomplished by relying only on the target position coordinates of all module cells and the tactile sensors on the six edges of each module [45, 49]. Figure 2 shows six snapshots of the planning process of the reconfiguration algorithm for a system consisting of 11 modules with a 0-cost path.

Zongwei Ren proposed a topology expression method for this type of robot and also optimized the conformal topology transformation using a genetic algorithm. However, due to the limitation of individual module degrees of freedom, this type of topology transformation method is difficult to be applied in practice [41]. Foreign Casal uses a separate planning strategy that decomposes the overall topology of the robot into sub-topologies to achieve self-reconfiguration. In this paper, the initial and target conformations are decomposed into sequential hierarchical structures, and the sub-structures of the initial conformation are separately manipulated to transform them into the corresponding components of the target conformation during the reconfiguration process. Albert proposes a modular robot representation method with labeled planar graphs and association matrices The vertices of the planar graph represent the four connection ports of a single module The six edges represent the internal connections of the vertices which also include the number of each module The association matrix represents the connection relationships of the modules in the configuration. Using this method can help to efficiently compile the data in the computer into understandable symbols.

3.1.2 Melting-Growth Self-Reconfiguration Strategy

Rus proposed a melting-growing (Melt-Grow) algorithm [50, 51] to achieve the disassembly and reconfiguration of modular robots with cubic shapes. The core idea of this reconfiguration strategy is that the initial configuration melts into a kind of chain-like intermediate configuration, and the conversion process from the target configuration to the intermediate configuration is taken in reverse to complete the growth process. Later, the Melt-Grow algorithm was improved by Fitch [52, 53] for solving the reconfiguration planning of heterogeneous self-reconfiguring robots under the sliding cube model. Despite the innovative nature of the scalable cube module design scheme and the Melt-Grow algorithm, there is a drawback, which is the problem of a centralized algorithm for reconfiguration control. As the number of cell modules composing the robot increases, the efficiency of the centralized algorithm decreases.

3.1.3 Distributed Execution of Self-Reconfiguration Strategies

Kotay et al. [54] from Dartmouth College, USA, studied the Molecule system using a distributed execution process based on a graph search algorithm to plan the path and then use the module's control algorithm to move along that path so that the individual modules move along the outside of the grid surface, which in turn completes the reconfiguration process of its robotic modules. The most advanced aspect of this algorithm is that the global reconfiguration algorithm of the molecular module is given in the form of a genetic algorithm. Figures 3 and 4 show the molecular execution sequences for concave transitions and convex transitions, respectively.

Bulter, Z et al. planned PacMan [55, 56], a distributed self-reconfiguration algorithm for the self-reconfiguration process of the Crystalline self-reconfiguring robot. First, a single module is informed about the target conformation and then the structural information of the target conformation is transmitted to all other modules using local communication. The next step is to execute the remainder of the algorithm in a distributed manner. The first step: finding the modules in the initial conformation that are in inappropriate positions and planning the path to the desired position in the target conformation. Next, the remaining atoms are searched for modules that can fill the adjacent gaps. Using a depth-first approach the target atoms transport an imaginary "planning ball" to their neighboring positions. In addition, the target

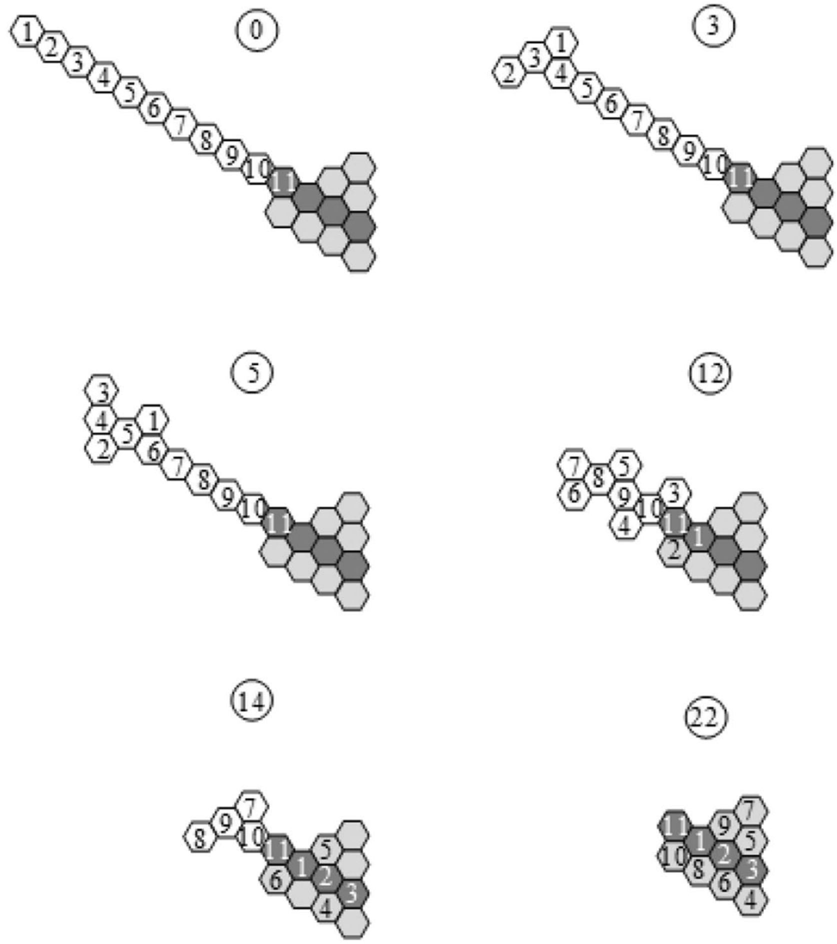


Fig. 2 Hexagonal System Reconfiguration Snapshot

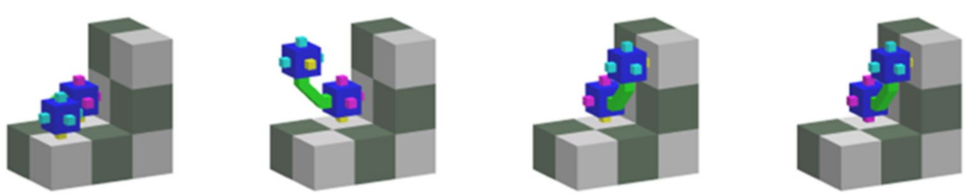


Fig. 3 A depressed transition sequence

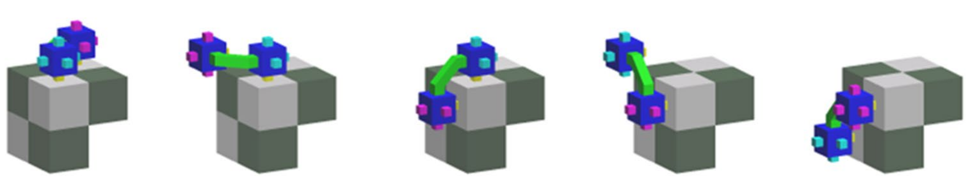


Fig. 4 Transition sequence of a convex surface

atom or the remaining atoms simply follow this path one step further and then exchange identities with the next module, repeatedly pushing different modules and finally pushing a module to the appropriate position in the target configuration. The natural parallelism of the PacMan algorithm allows for improved reconfiguration performance, making it possible to perform much faster than a central controller for systems with a large number of modules. PacMan can successfully execute in parallel any path set that does not contain cycle path sets and does not suffer from deadlocks in the presence of cycles.

(2) Yanqiong Fei and Zhenxing Xia [22, 23] used feature vector matrices [38] to study and investigate a reconfiguration strategy for the distributed control robot M-Cubes [22, 57, 58]. The strategy is based on the principle of proximity filling, using the distance between the center of gravity of the current configuration and the center of gravity of the target configuration as a function of the information inspired by the motion of each module, combined with the analysis of the possible motion space of each module itself, driven by the center of gravity difference, planning the movement of the module to a reasonable motion space, achieving the current configuration to the target space gradually filling approximation, and combining the characteristics of the module motion this algorithm is The algorithm is optimized by combining the characteristics of module motion. A simulation platform was also established using JAVA 3D language to simulate the self-deformation process of a simple system, as shown in Fig. 5.

3.1.4 Self-Reconfiguration Strategy for Auxiliary Module Groups

(1) Kaiyuan Liu et al. proposed a reconfiguration strategy based on auxiliary module groups to realize the reconfiguration between module chains of different configurations [44]. The two module units that form the auxiliary module group can be alternately used as the motion module and the transfer module, and the L-shaped displacement unit is formed by using any adjacent module or support as the fixed module to realize the movement of the auxiliary module group. Define the minimum number of modules and standoffs on the connection path between the current module and the target module as the depth of the current module. Using the module at the end of the module chain as the starting point and marking the depth at the starting point as 0, the breadth-first search algorithm is used to traverse all modules and supports in the system. The modules and supports connected with depth 0 are marked with depth 1, then the modules and supports connected with depth 1 and not yet marked with depth 2, and so on, until all modules and supports are traversed and marked with depth. In this way, the depth value of any module and support relative to the target coordinate will be decreased strictly according to the extension direction of the module chain, and the smaller the depth value, the closer the module is to the target point along the extension direction of the module chain. When the depth value is 0, it means that the module has reached the target coordinate point, Fig. 6 shows the auxiliary module group.

(2) Wei Hongxing and Li Haiyuan [42] proposed a self-assembled group modular robot (Sambot) that combines the characteristics of self-reconfiguration and group robotics and used MSRS to build a simulation platform to model the Sambot robot system. The proposed docking and self-assembly algorithms were validated using MSRS and optimized. Then, the self-assembly tests were performed on the real platform to verify the sensor functionality, algorithm efficiency, and reliability, Fig. 7 illustrates the autonomous docking of 2 Sambot, and Fig. 8 shows a scenario in which the structure of a group of robots is reorganized to adapt itself to the terrain, where they can autonomously form a serpentine morphology to pass through obstacles. The self-assembly process simulation is built in MSRS simulation environment according to realistic robot parameters and physical environment, where the self-assembly algorithm can be verified and the control parameters can be dynamically optimized according to the simulation effect.

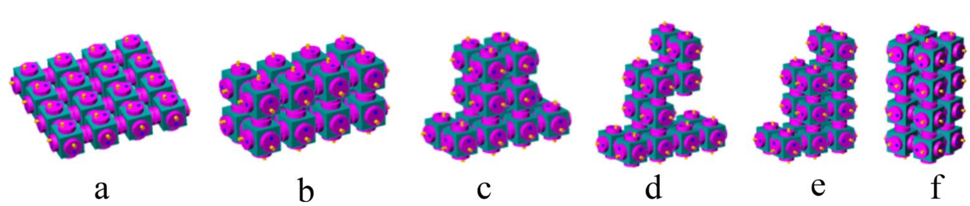


Fig. 5 M-Cube System Self-Variant Simulation

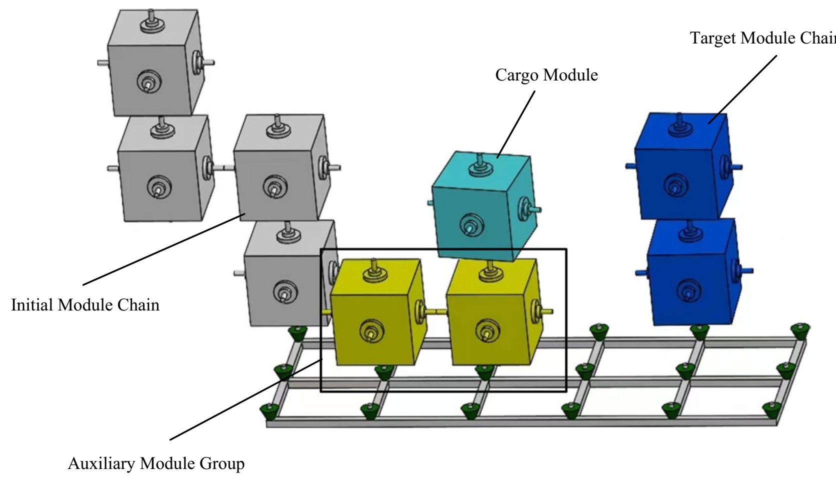


Fig. 6 Auxiliary module group

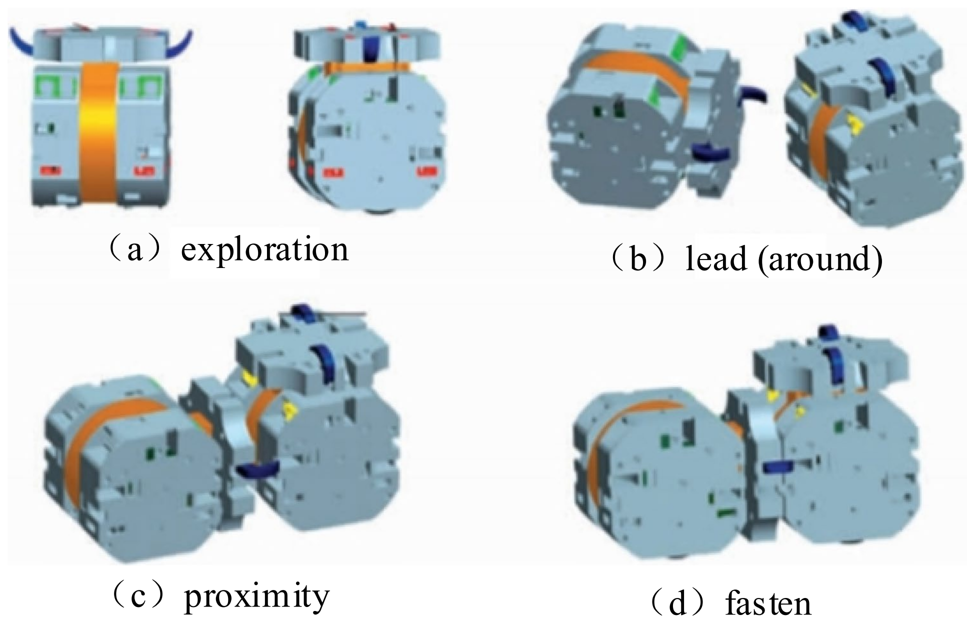


Fig. 7 Schematic diagram of 2 Sambot Autonomous Docking

3.1.5 Fully Discrete Local Intelligent Self-Reconfiguration Strategy

(1) Wei Xu proposed an effective unified description model of topology for the basic characteristics of various self-reconfiguring robot system structures using the PATTERN model as a platform and proposed a fully discrete local intelligent self-reconfiguration strategy in combination with this description model [59, 60].

An effective descriptive model is first proposed that can determine the global topology of the robot from the local sensory information of each module as a basis for generating a self-organizing control algorithm, and then a purely logical rule is proposed to generate a control algorithm in which the robot module performs parallel computation based on the information of local interactions and obtains a reasonable sequence of motions by determining and evolving rules to constrain the motion of the module cells to generate a global self-organizing behavior. This reconfiguration strategy can enable a self-reconfiguring robotic system to act on its own according to predetermined rules and produce reasonable motions and deformations under certain constraints in the absence of global intelligent control information and the absence of predetermined information about the environment and the task, and has been validated by simulations with robot overrunning motions [30, 59, 60], Fig. 9 shows the self-organized barrier crossing process of a 15-module morphing robot. The principle of self-organized deformation of self-reconfiguring robots with fault tolerance, this topological deformation principle based on discrete intelligence

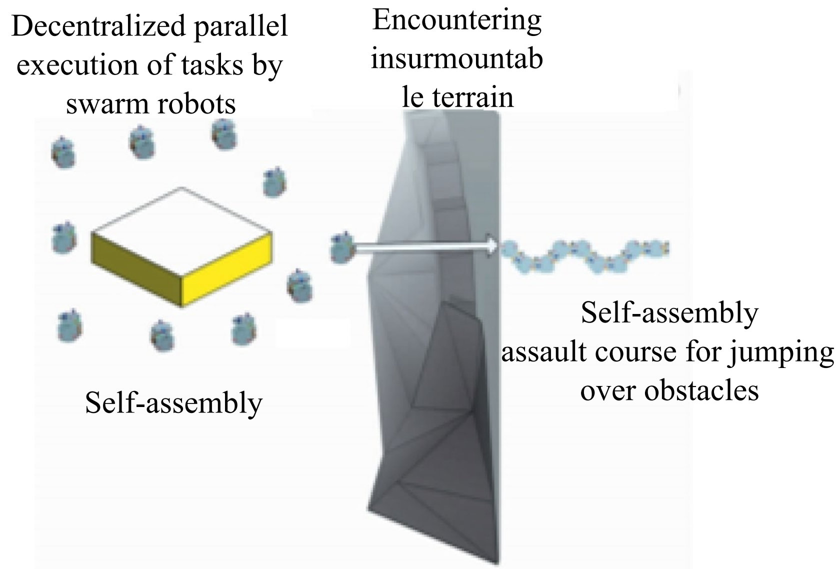


Fig. 8 Swarm robots self-assemble into snakes to cross obstacles

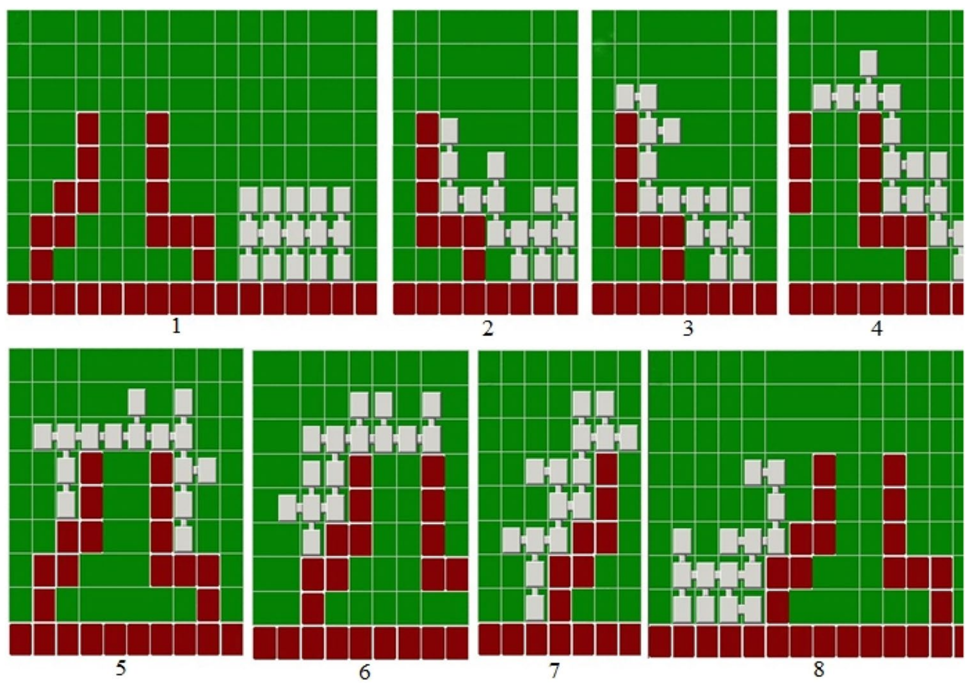


Fig. 9 Self-organized barrier-crossing process of a 15-module morphing robot

can be applied to various types of self-reconfiguring robotic systems with homogeneous modules, and various forms of self-reconfiguring robotic systems such as obstacle-crossing robots and deformable spacecraft for aerospace applications are designed.

3.1.6 Environment-Constrained Self-Reconfiguration Strategy

(1) For its UBot prototyping machine module, Pijun Liu [61] locates the self-reconfiguration deformation problem from environmental adaptation and task needs under a distributed control framework, and transforms the traditional deterministic reconfiguration oriented to a specific target configuration into a self-reconfiguration deformation strategy oriented to environmental constraints and task guidance. A virtual casting deformation planning method oriented to environmental requirements is proposed to develop a virtual mold of the target configuration and achieve overall reconfiguration by flow filling into the mold. The fractal reconfiguration deformation planning algorithm is proposed for specific tasks, which can ensure the coordinated

motion capability of reconfigured structural configurations.

This distributed motion coordination control algorithm based on excitation pulses enables reconfigured configurations with certain configuration characteristics to automatically generate conformation-compatible motion, and the effectiveness of this distributed algorithm was verified by worm configuration coordinated motion experiments [62]. Figure 10 shows the motor gait of the worm conformation. However, although this algorithm can solve the coordinated motion generation of configurations, it has limitations on the topological characteristics of configurations, and how to solve the coordinated motion generation of arbitrary configurations with motion capabilities will become an important direction for further research.

(2) Ren Zongwei et al. proposed a centralized hierarchical reconfiguration strategy based on dynamic subunits for the UBot [37] modular robot system. The strategy transforms the target-specific configuration-oriented reconfiguration into task-guided self-reconfiguration deformation under environmental constraints [24, 63], and finally realizes the configuration change. The designed hierarchical motion planning strategy can accomplish automatic planning of the moving process of a conformation composed of "windmill"-shaped subunits according to certain rules. The algorithm is adapted to the case where the number of "windmills", the basic unit of the conformation composition, changes and has a strong scalability. Figure 11 shows the simulation process of this strategy.

Table 1 summarizes several of these raster reconstruction strategies, comparing their characteristic.

3.2 Chain Self-Reconfiguration Strategy

For the chain reconfiguration strategy, the robots of this type of strategy are free from the constraints of the grid in terms of movement and connection, and can reach an arbitrary position within the workspace by planning and realize deformation reconfiguration by docking and separating between the module chains. This makes the reconfiguration strategy not only limited to a single module, but the movement of the whole chain, thus greatly increasing the complexity of the reconfiguration strategy.

The problem of self-reconfiguration for chained robots was first studied by Yim and Casal et al. [8, 66–68]. The Divide-and-Conquer self-reconfiguration algorithm was proposed for the Polybot [69] system, which uses centralized control to match the current configuration with the target configuration in a hierarchical manner. The matching of the two configurations is quantified into five cases according to the specified hierarchical differences, namely the number of layers, the number of layer modules, the size of the substructures in each layer, the type of the substructures in each layer and the connection points with the parent module, and the matching of the above cases is performed step-by-step according to the sequence of motions, which is currently limited to simulation studies. The following are the main chain reconfiguration strategies for self-reconfiguring robots at present.

3.2.1 Hormone-Distributed Self-Reconfiguration Strategy

(1) W.M. Shen proposed a hormonal distributed control method to implement self-reconfiguration processes and gait control [70–74]. The motion process is shown in Fig. 12. The hormones are transferred between modules and the overall movement is generated by activating the corresponding actions and other hormonal information. This method has no planner and the hormones are manually programmed to solve the specific self-reconfiguration task of the CONRO tandem robot,

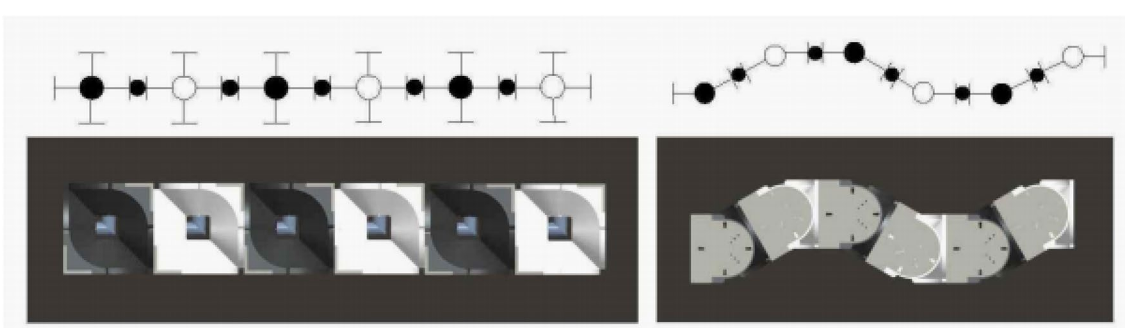


Fig. 10 Typical movement gait of the worm configuration

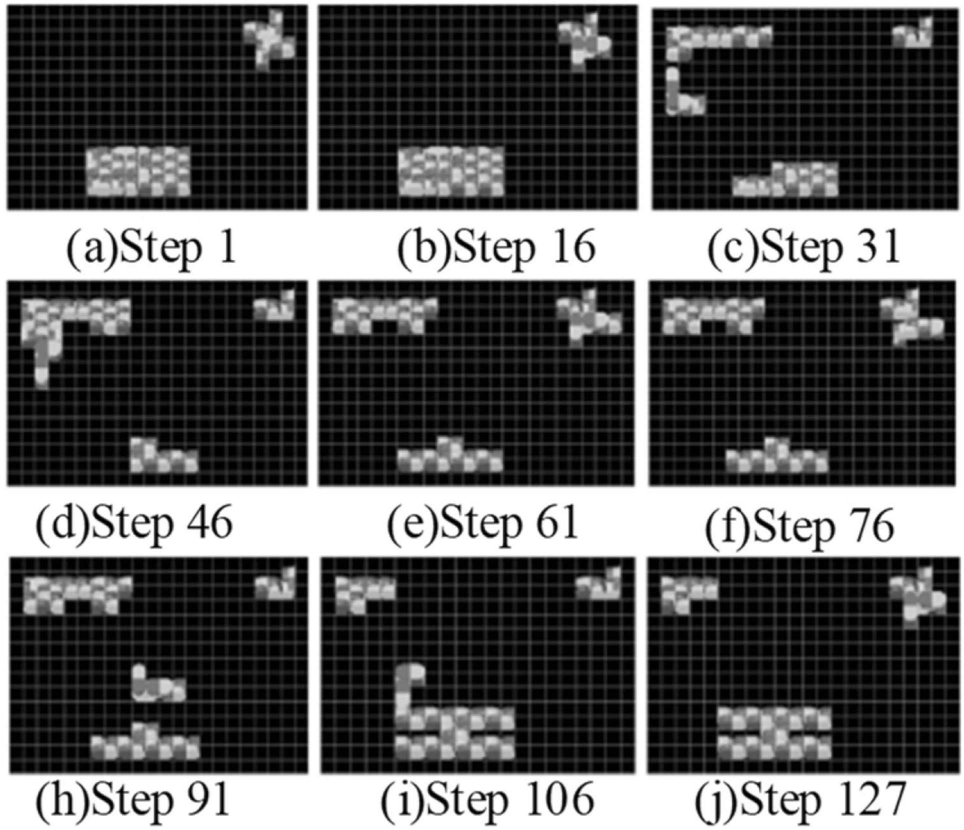


Fig. 11 Self-reconfiguring emulation process

so it is programmed for a specific reconstruction task and lacks some universality, making it difficult to apply to other self-reconfiguration systems.

(2) Nelson [75, 76] used a graph-theoretic representation to study the reconfiguration of a chain modular robot. First, an analytical approach combined with a standard measure of bipartite graph matching theory was used to find the largest identical subgraph in the graph-theoretic representation of the initial and target configurations; the reconfiguration campaign was then started. Figure 13 shows the flow chart of the reconfiguration algorithm. Although claimed to be close to the optimal graph matching algorithm, no feasibility analysis and proof are mentioned. Kinematic and load limitations should be considered in the selection of reconfiguration steps, and modular systems are limited by connections and modular chains, which are difficult to apply to all chained modular robots.

3.2.2 Connection-Motion Two-Level Self-Reconfiguration Strategy

To solve the self-reconfiguration problem of tandem self-reconfiguring robots, Deng Jianping proposed a self-reconfiguration planning algorithm based on a two-level planner for connection and motion [77]. Figure 14 shows the simulation of the reconfiguration strategy. The connection planner completes the transformation of conformations in the ideal topological space, it first treats the two conformations as two points in the topological space and then finds a line segment connecting the two points, i.e., it finds a series of intermediate topologies to complete the transformation of the two conformations, the transformation of two adjacent topologies can be completed with just one separation or connection between modules, and the output of the connection planner is a series of sequences of separation and connection between modules. This sequence is passed to the movement planner, which then performs each connection or separation action in this connection sequence sequentially in the Cartesian coordinate system, generating and outputting a sequence of module movements to compute feasible movement strategies for all modules included in each connection step.

3.2.3 Heuristic Search Self-Reconfiguration Strategy

(1) Asadpour [78, 79] proposed a self-reconfiguration planning method based on heuristic search, where graph signatures theory (GST) is used for inter-configuration reconfiguration and the maximum identical graph between configurations is used as a heuristic function to guide the search to find the respective reconfigura-

Table 1 Comparison of Strategies

Strategy Name	Description	Features	Literature
Hierarchical self-reconfiguration planning algorithm self-reconfiguration strategy	This algorithm is to divide the self-reconfiguration planning task into multiple steps or levels of completion	Flexibility in choosing the intersection between initial configuration and target for maximum efficiency in reconfiguration	[41, 46, 47, 64, 65]
Melting-growth self-reconfiguration strategy	The core idea of this reconstruction strategy is that the initial conformation melts into a kind of chain-like intermediate conformation, and the conversion process from the target conformation to the intermediate conformation is taken in reverse to complete the growth process	is highly innovative, but the efficiency of the centralized algorithm decreases as the number of cell modules that make up the robot increases	[50–53]
Distributed execution of self-reconfiguration strategies	A distributed execution process based on a graph search algorithm plans the path and then uses the module's own control algorithm to move along that path	The advanced point is that the global reconstruction algorithm of the molecular module is given in the form of a generic algorithm, but it is not completely solved for some of the problems mentioned above	[22, 54, 55]
Self-Reconfiguration strategy for auxiliary module groups	The strategy's auxiliary module group contains two modular units for the motion and transfer functions, respectively	Enables reconfiguration between chains of modules of different configurations	[42, 44]
Fully discrete local intelligent self-reconfiguration strategy	The robot module performs parallel computation based on local interaction information to constrain the motion of the module cell by determining and evolving rules to obtain a reasonable motion sequence and produce a global self-organized behavior	It can make the robot act on its own under certain constraints according to predetermined rules to produce reasonable motion and deformation	[30, 59, 60]
Environment-constrained self-reconfiguration strategy	Environmentally oriented virtual casting deformation planning method to develop virtual molds of target configurations and achieve overall reconfiguration by flow filling into the mold	This strategy can solve the coordinated motion generation of the configurations but has limitations on the topological characteristics of the configurations	[37, 61]

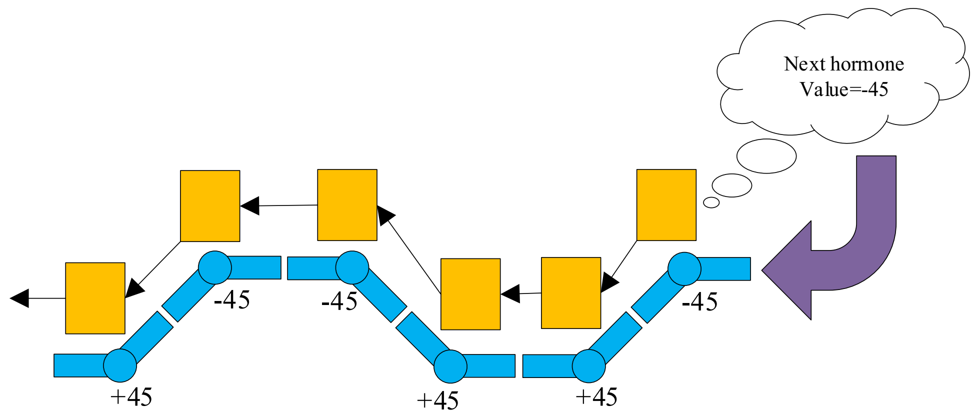


Fig. 12 Hormone-based control of worm movement process

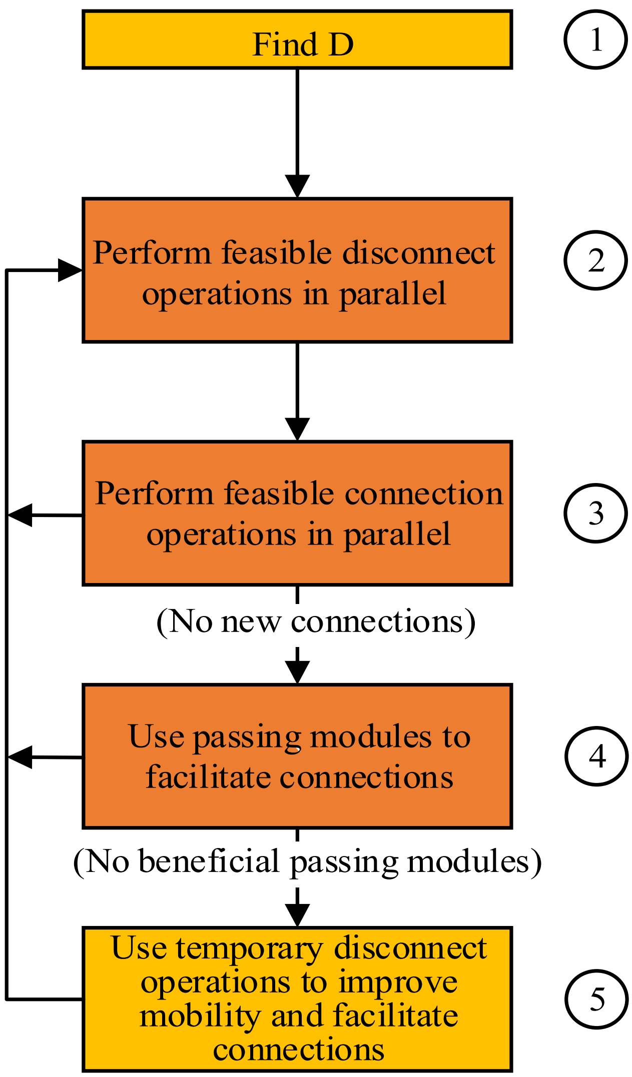


Fig. 13 Reconfiguration algorithm flow chart

tion path for each module. Although the algorithm can achieve reconfigurations from quadrupeds to snakes as shown in the Fig. 15, the heuristic cannot be applied in general cases because his computation is very slow and cannot be extended to more modules. In robots with more modules, the configuration space and reconfiguration motion space are too large, so this search method may not find a solution in a reasonable amount of time.

(2) Yoshida proposed a hierarchical planning method for reconfiguration planning of M-TRAN III with centralized planning control [21, 54, 80, 81], and the algorithm consists of two parts: the global planner at the upper level and the local motion scheme selector at the lower level. The global planner is responsible for solving the overall motion trajectory; the motion scheme selector selects an effective motion scheme based on the results of the global planner and the current local connection state to complete the motion of the module. In solving the motion planning problem, an evolutionary motion synthesis planning method using a genetic algorithm is proposed, which realizes the self-reconfiguration simulation of the chain structure. Figure 16 shows the simulation process.

3.2.4 MorphLine Self-Reconfiguration Strategy

Based on graph theory and search algorithms [33, 65], Feili Hou proposed a reconfiguration strategy called MorphLine to study the reconfiguration planning problem of SuperBot, using the number of module connections for configuration matching and motion planning, by which the robot can automatically and quickly change from any one configuration to any other configuration in a distributed way. Figure 17 shows an example of the refactoring process. However, the algorithm only stays at the theoretical level and does not incorporate the spatial configuration information as well as consider the spatial alignment of the module assembly and the limitations imposed by the module motion capability on the spatial branch chain docking, so it cannot accurately accomplish the spatial configuration reconfiguration task.

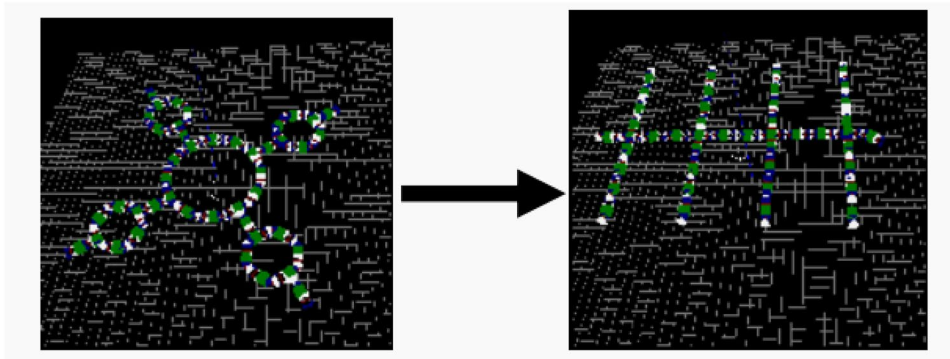


Fig. 14 Refactoring Example

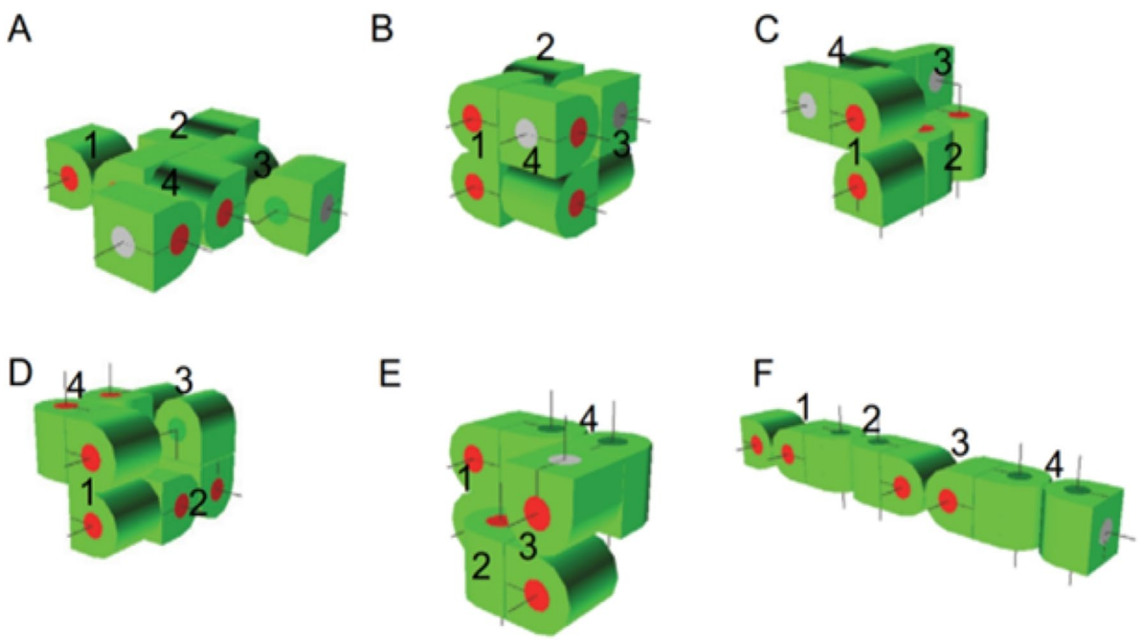


Fig. 15 Reconfiguration of tetrapod to serpentine

In addition, the configuration matching process has certain constraints and cannot perform deep and comprehensive matching work.

3.2.5 Space Deformation Line Self-Reconfiguration Strategy

Zhao Teng et al. proposed a novel spatial deformation line self-reconfiguration strategy for chain module configurations [64]. This strategy, with the help of the depth-first search algorithm, designs the assembly information collection principle so that the assembly identification between each connected module is completed autonomously, and automatically generates the SAM matrix to obtain the AN value of each module in the configuration to complete the configuration identification work. Deep configuration matching is used to establish the corresponding module matching relationship between two configurations through index information, and the configuration matching is completed by each module in a distributed manner, using the double matching principle to ensure the efficiency and accuracy of the matching work, and the depth matching method is applied to lock the reconfiguration task area and reduce the number of modules involved in a reconfiguration to find the optimal reconfiguration path and improve the reconfiguration efficiency. Finally, the break-joint position and the module branch chain motion are determined by two-step chain spatial reconfiguration motion planning. Figures 18 and 19 show the flow chart of linear reconstruction and target reconstruction.

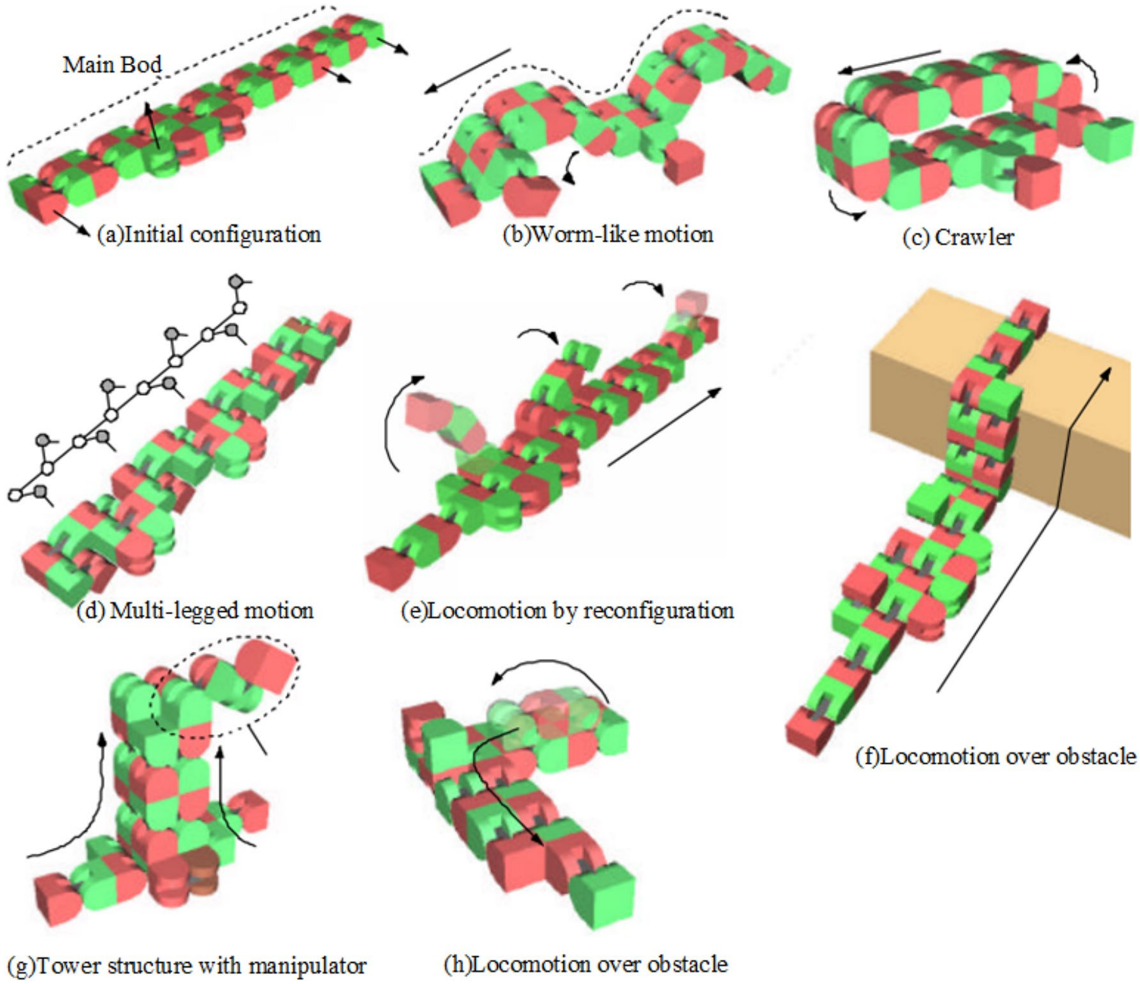
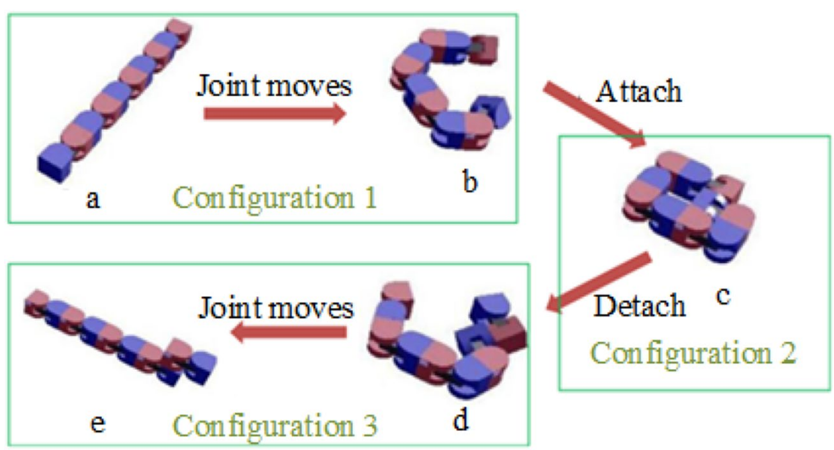


Fig. 16 Reconfiguration and motions

Fig. 17 Example of the refactoring process



3.2.6 Hierarchical Reconfiguration Planning Self-Reconfiguration Strategy

(1) Interj. Liu proposed a hierarchical reconfiguration planning method [8, 82], in which the reconfigurable determination algorithm was first used to search for variable configurations of any configuration to combine them into a cluster, called the self-reconfiguration group of the robot, and then all the configurations within the self-reconfiguration group and the variation

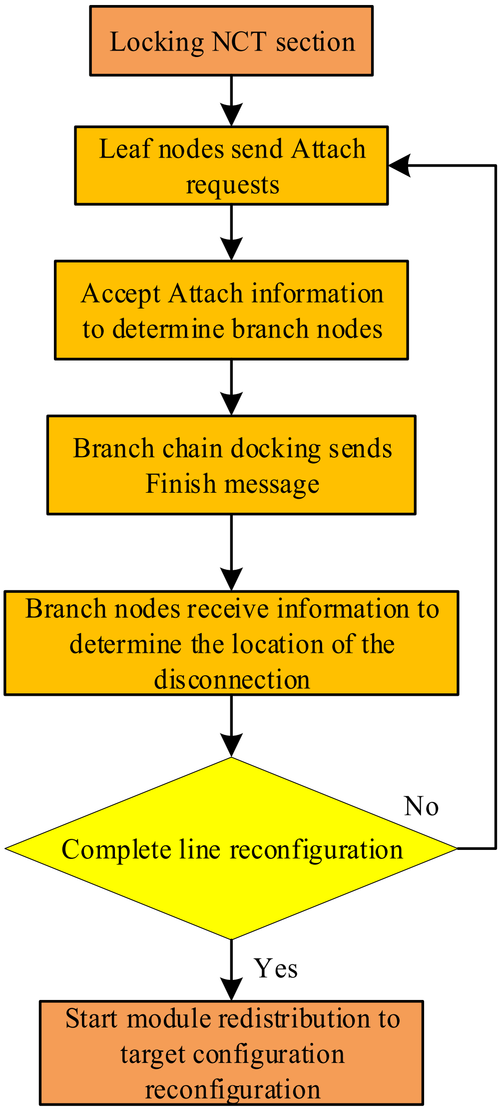


Fig. 18 Line Reconfiguration Flow Chart

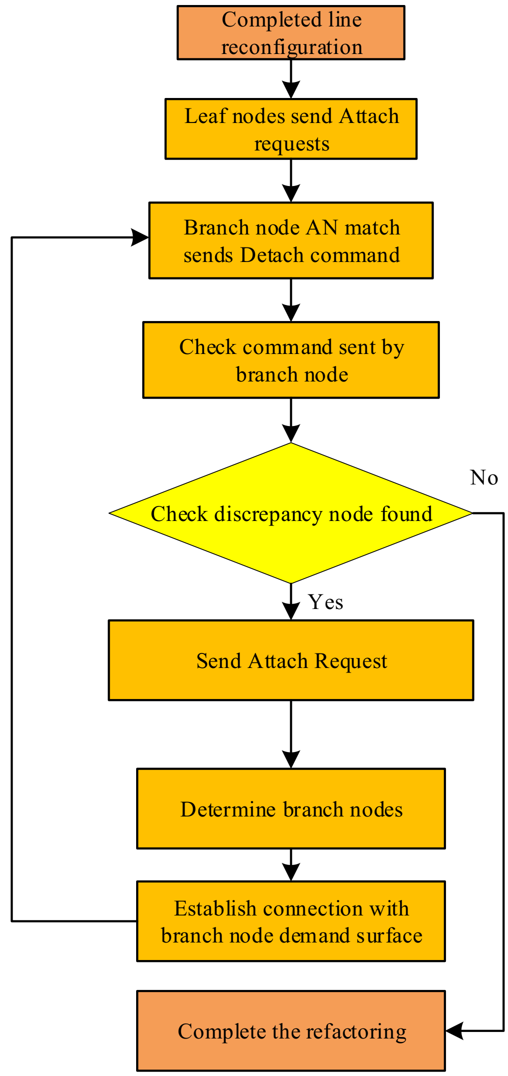


Fig. 19 Flow chart of goal reconstruction

relations between configurations were expressed by a graph of configuration reconfiguration relations, and the optimal reconfiguration path between any two configurations was found with the help of the shortest path planning method in graph theory. Then the hierarchical reconfiguration planning of the self-reconfiguring robot is realized by combining the obtained reconfiguration process, to realize the configuration transformation of the modular robot, Fig. 20 is a schematic diagram of the reconfiguration. The algorithm is computationally intensive, and it is difficult to find the reconfiguration paths in the case of a large number of robot modules.

(2) Huajin Zhang et al. proposed a hierarchical parallel reconfiguration strategy for the novel movable spatial multi-angle self-reconfiguring robotic cell module MSMAbot [29]. Firstly, the configuration identification of the robotic system containing the toroidal branch chain is performed by the bounded depth-first search algorithm BDFS. Secondly, the address definition and configuration identification of each module is completed by module traversal of the initial and target configurations, and the spatial connection information matrix group SCIMG is obtained, which accurately provides a complete spatial information representation of the self-reconfiguring robotic system of any configuration, and the optimal matching between configurations is obtained by SCIMG of two configurations. Finally, the system locks the optimal common topology based on the optimal topology matching of configurations and module mapping results and then implements reconfiguration planning for the non-common topology part, following the rules of connecting before disconnecting and reconfiguring multiple branch chains in parallel

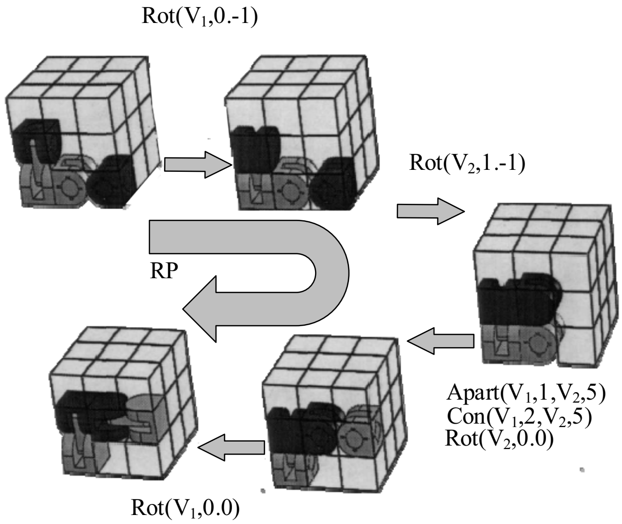


Fig. 20 Schematic diagram of the reconfiguration process

to determine the locations of the initial configurations that need to be disconnected and connected to realize the transformation between different configurations, Fig. 21 shows the reconfiguration process diagram.

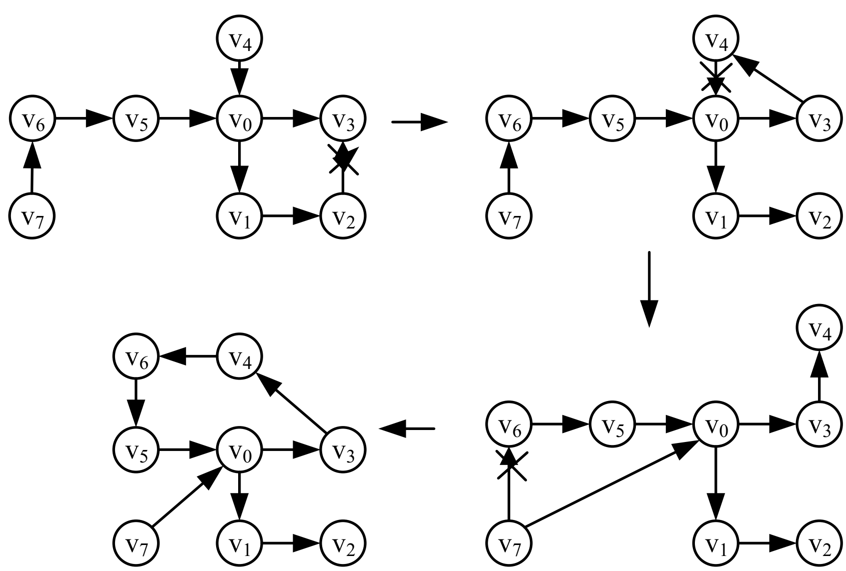
(3) Hongan Yang, Jie Kong, Shuai Cao, Wenpei Gong, and Gaopan Shen from Northwestern Polytechnic University [83] proposed a new molding method for flexible deformation of robot systems with tasks, called distributed cluster robot chain molding method, based on the local interaction and autonomous collaboration of distributed, large-scale lattice cluster robots for operational tasks in complex nonstructural environments.

As there are a large number of individual robots in the large-scale cluster system, how to plan the movement priority of individuals, avoid blocking and collision during robot movement, and ensure the formation of the expected shape in an orderly and stable manner is the primary problem of autonomous forming of the cluster system. Combining the characteristics of lattice-type systems, a hierarchical forming strategy is proposed to transform the global behavior of large-scale cluster forming into the local behavior of individuals in the outer layer of the current cluster, which completes the autonomous planning of robot movement order and also makes the complex group forming process simple.

For the two-dimensional target configuration task set by the user, a hierarchical shaping strategy of "peel off, fill in, and iterate cycle" is proposed under the condition that all individuals of the cluster robot are gathered and aligned, as shown in Fig. 9. Driven by this strategy, the outermost individuals of the cluster are filled into the target area in an orderly manner by a kinematic chain after the initial configuration and the target configuration have completed the layering process, and this iterative cycle is car.

In Fig. 22, after matching the combination of the initial and target conformations, the entire conformation is divided into three regions and one layer: the region outside the target conformation body, the region inside the target conformation body, the region to be filled and the edge layer inside the region to be filled (Fig. 22a). On this basis, based on the layered peeling strategy, the set of robot individuals that move preferentially within the current aggregation is planned through the local interactions between individuals within the edge layer of the robot aggregation, and the shaped motion chain is constructed (Fig. 22b). Based on the hierarchical filling strategy, the robotic individuals within the kinematic chain move along the aggregation boundary

Fig. 21 Reconfiguration process diagram



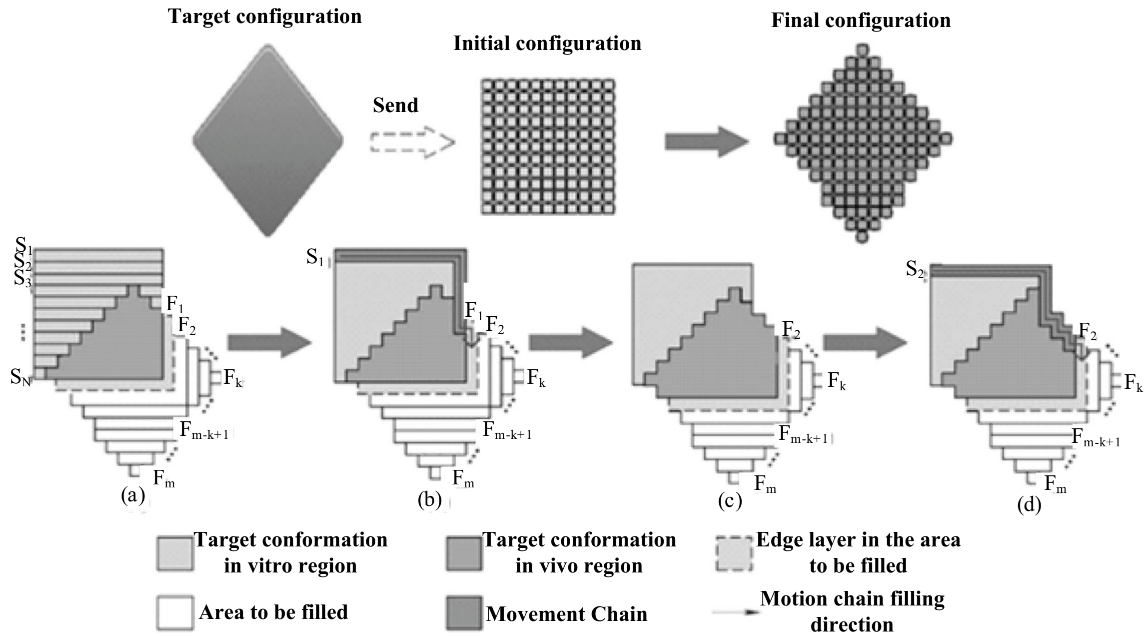


Fig. 22 Diagram of autonomous forming strategy for cluster robots

and fill the edge layers within the region to be filled in turn (Fig. 22c). When the filling of individuals in the kinematic chain is finished, new kinematic chains are continuously excited and filled into the region to be filled according to the iterative cycle strategy until the target configuration task is completed (Fig. 22d).

Table 2 summarizes the above-mentioned chain reconfiguration strategies, comparing their characteristics.

4 Discussion

The efficiency, energy consumption and application range of the reconfiguration strategy of a self-reconfiguring modular robot are the criteria for evaluating the strategy, the higher the efficiency, the lower the energy consumption, and the wider the application range of the strategy means that the strategy is better, but it is difficult to satisfy all the three at the same time in the current research, and it can only satisfy two of them at the same time or focus on only one.

In this section, we compare the above self-reconfigurable modular robot reconfiguration strategies and analyze them in terms of reconfiguration efficiency, application scope, and energy consumption, which are visually illustrated in a table graded from one (low level) to five (high level). The higher the efficiency, the higher the level, the wider the application range, the higher the level, and the lower the energy consumption, the higher the level.

4.1 Grid Format

4.1.1 Analysis of Hierarchical Self-Reconfiguration Strategy

Searching out the maximum common topology of the initial and target conformations before the conformational transformation can effectively improve the self-reconfiguration efficiency of the self-reconfiguration robot, and can also effectively control the energy consumption. However, if the number of modules increases, the maximum common topology may be deviated and does not achieve the expected effect.

4.1.2 Analysis of Melt-and-Grow Self-Reconfiguration Strategy

Many improvements at the cost of increased computational steps to reduce the number of moves and partial efficiency to reduce energy consumption.

4.1.3 Analysis of Distributed Execution Self-Reconfiguration Strategy

This strategy has the advantages of computational ability, communication ability, low energy consumption and high control accuracy. It can perform various tasks such as locomotion, structure formation and dexterous movement with a large scope of application. The efficiency is on the low side.

Table 2 Strategy Comparison

Strategy Name	Description	Features	Literature
Hormone-distributed self-reconfiguration strategy	The purpose of producing overall movement is achieved by activating the corresponding movements and other hormonal information	Lack of certain universality, difficult to apply to other self-reconfiguring systems	[70, 74]
Connection-motion two-level self-reconfiguration strategy	The work of conformational change is divided into two phases, which are performed by two functional modules	The specific selection method of the substructure, the specific selection of the reconstruction algorithm and the decomposition of the constrained conformation are not solved	[77]
Heuristic search self-reconfiguration strategy	The maximum identity graph between configurations is used as a heuristic function to guide the search to find the respective reconfiguration path for each module	Reconfiguration from quadrupeds to snakes is possible, but the computation is very slow and does not scale to more modules	[78–81]
MorphLine self-reconfiguration strategy	With this strategy robots can automatically and quickly change from any one configuration to any other configuration in a distributed way	Only at the theoretical level, the task of spatial configuration reconstruction cannot be done accurately	[33, 65]
Space deformation line self-reconfiguration strategy	The assembly identification between each connected module is completed autonomously, and the SAM matrix is generated automatically to obtain the AN value of each module in the configuration to complete the configuration identification work	The use of the double matching principle ensures efficient and accurate matching work reconstruction efficiency	[64]
Hierarchical reconfiguration planning self-reconfiguration strategy	The variation relationship between configurations is expressed by a configuration reconstruction relationship diagram to find the shortest path and use hierarchical reconstruction planning	The algorithm is computationally huge and it is difficult to find reconfiguration paths in the case of more robot modules	[8, 29, 82, 83]

4.1.4 Analysis of Self-Reconfiguration Strategy of Auxiliary Module Group

It is a strategy driven by the fastest depth descent method, which requires less computational resources and is more efficient, because it requires specific auxiliary modules, and the scope of application is more limited.

4.1.5 Analysis of Full Discrete Local Intelligence Self-Reconfiguration Strategy

This topology deformation principle based on discrete intelligence can be applied to all kinds of self-reconfiguration robot systems with isomorphic modules, which has a wide range of application, but because it is a discrete topology deformation, it may cause the module to do some ineffective actions, which increases the energy consumption and reduces the efficiency of reconfiguration.

4.1.6 Analysis of Environment-Constrained Self-Reconfiguration Strategy

The motion strategy can not only move in the plane, but also adapt to the gullies and other complex environments, with a small search space, solution efficiency, etc., it is an effective and feasible planning strategy, but the deformation shape of the strategy has limitations, limited by environmental constraints, and it can't be converted into any configuration.

4.2 Chaining

4.2.1 Analysis of Hormonal Distributed Self-Reconfiguration Strategy

It is a generalized control algorithm for controlling the motion of a self-reconfiguring robot. The algorithm has the following properties: distributed, scalable, homomorphic, and minimized. It is currently not applicable to general robotic systems. However, the concept of "connectors between modules" can be generalized to "communication channels between robots" and applied to control collaboration between distributed robotic systems in dynamic networks.

4.2.2 Analysis of Two-Level Self-Reconfiguration Strategy of Connection-Motion

We need a sensor model with higher precision and a certain degree of effectiveness, and study the corresponding docking algorithm according to the new sensor model, which can be applied to a certain range of self-reconfiguration modular robots, with high precision and good reliability, but with low efficiency.

4.2.3 Heuristic Search Self-Reconfiguration Strategy Analysis

Based on the editing distance of the graph and the shortest path length from the initial configuration to the current configuration, a heuristic function is used in the guided search to find a feasible solution, which is less efficient, consumes less energy, and has a larger range of applicability, and at the same time has a relatively low reliability, depending on the quality of the searched graph.

4.2.4 Analysis of MorphLine Self-Reconfiguration Strategy

The goal configuration is not to produce any pre-planned action steps, this strategy is not limited to any specific hardware design of chain modules and is applicable to all chain reconfigurable robots in general, in some cases there are redundant actions that increase energy consumption and reduce efficiency.

4.2.5 Analysis of Self-Reconfiguration Strategies for Spatially Deformed Lines

Apply the depth matching method to lock the reconfiguration task area and reduce the number of modules involved in the reconfiguration to find the optimal reconfiguration path and improve the reconfiguration efficiency, but it requires specific branched-chain modules and is not applicable to most chain-type reconfigurable robots.

4.2.6 Analysis of Self-Reconfiguration Strategy for Hierarchical Reconfiguration Planning

It only needs to reconfigure the non-common topology part of the initial configuration and the target configuration, which saves the reconfiguration time, improves the efficiency and reduces the energy consumption, but as the module rises, the non-common topology part may not be the optimal solution.

5 Conclusion

Self-reconfiguring modular robots can be better applied in non-structural environments because of their ability to change configurations autonomously, thus attracting a wide range of research by scholars at home and abroad. In this paper, the reconfiguration strategies of self-reconfiguring modular robots are reviewed according to the existing research progress, and the grid-based and chain-based reconfiguration strategies are clearly introduced with their respective characteristics, and compared in terms of reconfiguration efficiency, energy consumption, and application scope.

(1) The research of reconfiguration algorithm based on grid constraints has been more perfect, compared with the chain modular robot, the lattice module has obvious advantages in the field of spatial reconfiguration planning algorithms, but can never get rid of the grid constraints, the reconfiguration space is relatively small, and the unit module can not be moved independently, which makes the process of reconfiguration complex, slow and inefficient. For the literature that exists today, different technical approaches are used to obtain efficient reconfiguration steps, however, there does not yet exist an optimal solution to ensure that the minimum number of reconfiguration steps is obtained. The unit modules of chained modular robots are free from the constraints of the grid in terms of reconfiguration motion and connections, and can reach any position within the range of their workspace through planning, and reconfiguration deformations can be realized through docking and disconnecting between modules. This makes the reconfiguration motion no longer limited to the movement of a single module but generates the movement of the whole branch chain, thus increasing the complexity of the reconfiguration strategy, and the universality is not high or some of them can only be limited to simulation studies;

(2) Most of the modular robots are powered by the battery system integrated inside, so optimizing the energy consumption of the whole cluster of modules is important to improve the sustained working capability of modular robots. Autonomous search and docking between dual modules can be understood as a shortest path problem between points, while the aggregation and reorganization of multiple modular robots is still an unknown field;

(3) Table 3 and 4 summarize and compare the main performance characteristics between the two types of strategies as well as between each strategy, from an overall point of view, the hierarchical self-reconfiguration strategy among the grid-format strategies has the best reconfiguration efficiency but does not use the majority of self-reconfiguring modular robots, the full-discrete-local-intelligent self-reconfiguration strategy is more applicable but its efficiency is on the low side, and is not suitable for robots focusing on efficiency work, and the melt-growth self reconfiguration strategy has the lowest energy consumption, but its efficiency and applicability are not high.

(4) From Table 3 and Table 4, it can also be seen that the efficiency of chained reconfiguration strategy is generally higher than the grid-format strategy, but the scope of application is lower than the grid-format strategy, this is because chained does not have the grid limitations of the grid-format, and can only be designed for a specific reconfiguration group of modules, which

Table 3 Performance comparison of raster format policies

Raster format type	Reconfiguration efficiency	Scope of application	Energy consumption
Hierarchical self-reconfiguration planning algorithm self-reconfiguration strategy	★★★★	★★★	★★★
Melting-growth self-reconfiguration strategy	★★★	★★★	★★★★
Distributed execution of self-reconfiguration strategies	★	★★★★	★★
Self-Reconfiguration strategy for auxiliary module groups	★★★	★★	★★★
Fully discrete local intelligent self-reconfiguration strategy	★	★★★★★	★★★
Environment-constrained self-reconfiguration strategy	★★★	★★★	★★

Table 4 Chained policy performance comparison

Chain type	Reconfiguration efficiency	Scope of application	Energy consumption
Hormone-distributed self-reconfiguration strategy	★★★	★★	★★
Connection-motion two-level self-reconfiguration strategy	★★★	★★	★★
Heuristic search self-reconfiguration strategy	★★★	★★★★	★★★★
MorphLine self-reconfiguration strategy	★★	★★★	★
Space deformation line self-reconfiguration strategy	★★★★★	★	★★★★
Hierarchical reconfiguration planning self-reconfiguration strategy	★★★★	★★	★★★★

improves the efficiency of the strategy and reduces the energy consumption, but it is not applicable to the majority of the robots.

Comprehensive analysis and summary of the research results of this paper on the reconfiguration strategy of modular robots, it can be seen that there is still a huge research space in the reconfiguration strategy, the future research on reconfiguration strategy needs to take into account a variety of factors to be carried out, the following is based on the proposed in this paper may be needed in the future to explore and research:

(1) Grid-format reconstruction strategy is relatively perfect, but the reconstruction process is more complex and less efficient, so how to simplify the process of grid-format reconstruction strategy and improve the efficiency is the next issue to be studied.
(2) The chain reconstruction strategy is more flexible than the grid format, but the algorithm will become more complex with the increase of modules, and its universality is lower, so the next research direction is how to improve the scope of application of the chain as well as to solve the problem of applying the strategy limited to simulation in practice.
(3) For the grid-format strategy, the next research can be carried out in terms of improving the efficiency and reducing the energy consumption, combining the ideas of the two reconfiguration strategies, or choosing one strategy combined with methods such as operations research to design a suitable reconfiguration strategy according to one's own needs.
(4) For chaining strategy, how to improve its applicability can be the next step to be studied, the current chaining strategy is more balanced is the heuristic search self-reconfiguration strategy, which can be referred to optimize the reconstruction efficiency performance under the premise of ensuring its applicability.

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Data Availability Not applicable.

Declarations

Ethics Approval The authors declare that this work is original and does not include experiments with animals.

Competing Interests The authors declare that they have no financial or non-financial conflict of interest.

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