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Path Planning Method in the Formation of the Configuration of a Multifunctional Modular Robot Using a Swarm Control Strategy

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***Abstract*—Multifunctional modular robots consist of a set of modules that can form a kinematic structure in accordance with the current task. When operating in a non-deterministic environment, the adaptive kinematic structure of the robot allows you to change the configuration and adapt to changing conditions and the limitations of the environment. However, the formation of the required configuration can take a lot of time, which is a problem when it is needed to perform the objective function in real time. Based on this, the purpose of this work is to reduce the time required for the formation of the modular robot configuration. The article proposes a method for path planning of moving modules when forming the configuration of a multifunctional modular robot using a swarm control strategy. This approach allows real-time information exchange between robot modules, and path planning accomplishes decentralized for each module, regardless of their number. The use of analytical geometry methods allows reducing the computational complexity of the method and avoiding the energy consumption of the onboard energy resources of the robot. The results of modeling the developed method for a robot consisting of 5-50 modules are presented.**

***Keywords*—modular robotics, path planning, formation of the configuration, group control, swarm intelligence**

I. Introduction

Modular Self-Reconfigurable Robots (MSRR) are robotic systems consisting of many different modules that interact with each other and exchange information to perform an objective function. MSRR consists of separate modules that have the ability to move relative to each other, creating different configurations [1, 2].

MSRR have the following distinctive features:

- Universality - used to perform a wide range of tasks.
- Reliability - in the event of a failure, the corresponding module can be replaced without interrupting the performance of the target task.
- Affordable price - the mass production of identical modules reduces the total cost.

Multilink construction is the principal feature that allows to talk about ensuring reliability, high adaptability of the structure, reconfigurability, its scalability, ability to self-repair, etc. in accordance with the specifics of the tasks to be solved in conditions of uncertainty of the environment, external disturbances and the state of its own subsystems. Such a set of functionalities implies the need to develop an intelligent control system with a distributed hardware structure that provides not only the movement of the robot in an a priori unknown environment, but also an automatic synthesis of the structure and control algorithms in self-learning mode [3]. The construction features and high functional flexibility determine a wide range of their possible applications: from the domestic sphere to solving special and combat tasks in the interests of law enforcement agencies; from operational creation of technologically sound structures to monitoring and research of spaces with limited access, research of the surface of planets of the solar system, etc. The implementation of such properties in specific samples of Modular Self-Reconfigurable Robots, which are of interest from the point of view of a number of practical applications, necessitates the development of intelligent control systems created on the basis of the integrated application of modern knowledge processing technologies and possessing a wide range of functionality [4].

When functioning in a non-deterministic environment, the adaptive kinematic structure of the MSRR allows changing the configuration and adapting to changing conditions and environmental constraints. However, the formation of the required configuration can take a lot of time, which is a problem when you need to perform the objective function in real time. The literature on the subject of research is represented by numerous developments in this area and is due to the relevance of the use of these developments in the modern world. The tasks arising from the development of solutions for the configuration of modular robots are discussed in the following papers [5-25].

The simplest and at the same time common approach to the path planning is the use of spatial decomposition method [5-9]. It involves dividing the free areas of the scene into many simple regions using one or another decomposition method, determining the adjacency of regions and forming a connectivity graph, which can later be used to navigate the scene. In fact, the approach implements a scheme for reducing the computationally complex motion planning problem in Euclidean space to a typical problem of finding a path in a graph. This approach showed high efficiency, but requires significant computational resources due to the need for detailed sampling of the entire stage space and ensuring acceptable accuracy of the path.

Sampling methods are used to reduce the computational complexity of the path planning algorithm. The essence of this approach lies in the study of areas of configuration space through repeated tests, the result of which is the decision on the admissibility of separately selected configurations. This procedure is carried out by generating random points, on the basis of which the route is built. An important advantage of the methods of this family is independence from the geometric representation and dimension of the simulated environment. The path planning task for modular robots with excessive degrees of mobility and diverse kinematic constraints can be solved using random tree methods [10-13]. The disadvantage of this solution is the impossibility of ensuring the optimality of the solutions found, and in the case of their absence, the algorithm can run for an infinitely long time.

A family of path planning methods consists of artificial potential field methods, originally developed for navigating mobile robots and bypassing local obstacles in real time [14, 15]. The methods are based on a physical analogy with the motion of a charged particle in an electrostatic field. The obstacles of the scene generate repulsive forces, and the target point of the route - a significant attracting force. The direction and speed of body movement are determined by the gradient of the potential field.

Over the past decade, many different optimization algorithms have been proposed for path planning, including genetic algorithm [16, 17], neural networks [18], particle swarming algorithm [15, 25], ant colony optimization [19, 20], A* algorithm [21, 22], Dijkstra's algorithm [23, 24]. In [15], a method for planning the path of modular robots based on a genetic algorithm was proposed. In this method, a population is randomly generated, whose chromosomes consist of various paths and configurations of a variable-length robot. The objective function can be defined by three criteria: the minimum travel time, the shortest distance, the minimization of energy consumption. In [16], the authors used a neural network to analyze the features of cartographic data and predict the difficulty of finding a route on a map. In article [17], the problem of optimizing the trajectory of a modular robot in the event of a module failure based on a particle swarm algorithm was studied. In this case, the optimization problem is reduced to the selection of the coefficients of the objective function. In [18], an algorithm for optimizing ant colonies was used to solve the task of planning the path of a mobile robot in complex environments. The coefficients of the algorithm were analyzed and selected for the operation of the robot in different working areas with obstacles of different numbers, sizes and shapes. The authors of [21] developed a path planning algorithm for a mobile robot using a genetic algorithm and the A* algorithm. The proposed algorithm includes three steps: the formation of a mobile robot model in space based on the MAKLINK graph, the search for an acceptable path for the robot to move using the Dijkstra algorithm, and the search for a global optimal path for a mobile robot based on the hybrid algorithm A* and the genetic algorithm. The paper [22] presents a solution for planning the shortest path for moving a robot in a maze based on the Dijkstra algorithm. The simulation results showed that the application of the proposed algorithm is effective when planning the path of a mobile robot in an environment with obstacles.

Analysis of existing solutions reflects the individuality of using the developed methods for a specific situation and device. Thus, path planning when shaping an MSRR configuration using a swarm control strategy is an important task.

II. Problem Formulation

The purpose of this work is to reduce the time required for the formation of the MSRR configuration. The main task is to develop a method for planning the path of movement of MSRR modules during configuration formation using a swarm control strategy.

The task of the study can be divided into three levels:

- Strategic planning level. At this level, the issue of global navigation is being addressed.
- Tactical planning level. The task of the tactical level is reduced to solving the problem of local navigation.
- Executive level. The task of this level is to provide the specified motion characteristics of the MSRRS module at each time point by means of drives.

Thus, to solve the problem, it is necessary to solve three subtasks: building global navigation through information exchange between MSRR modules using a swarm control strategy, building local navigation for configuring, building a motion control system for MSRR modules. The mathematical formulation of the problem is as follows: it is necessary to determine the target position q'_i of each MSRR module in order to form the required configuration with the known own position q_i and the given configuration P.

III. Methods

A. *Information exchange between MSRR modules using a swarm control strategy*

Each robot $m_i \in R$, $i = 1, 2, \dots, M$, where M is the number of robots in the group, is able to perform some limited set of elementary actions $A = a_1, a_2, \dots, a_b$. The

MSRR module $m_i$participates in the exchange of information with neighboring modules $m_j \in Q$ that are within range of a limited radius L:

$$Q = \{m_j \,\|q_j - q_i\| < L;\ j = \overline{1,N}\}. \quad (1)$$

Methods of swarm interaction in large groups of robots implement strategies for decentralized control of robots, where each robot independently decides on its actions based on the available information [6]. Each member m_i of the group receives information by communication channel $c_{i,j}$ only from a few neighboring robots m_j of the group located in the visibility zone of the robot m_i, that is, in the area of space limited by the radius of visibility of the robot L. An example of information exchange between MSRR modules when using a swarm control strategy is presented in Figure 1.

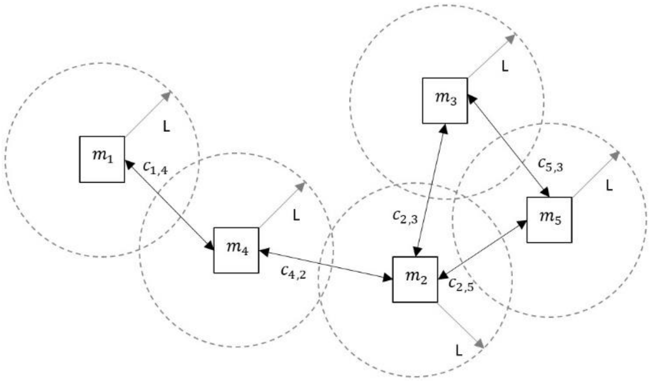

Fig. 1. Information exchange between MSRR modules using a swarm control strategy

With this approach, the amount of information transmitted between robots of the group in sight, as well as the time for selecting group actions do not depend on the total number of robots in the group, which makes it promising to use these methods to control large groups of robots numbering hundreds and even thousands of robots. This strategy of information exchange in the group allows you to avoid the energy costs of onboard energy resources of robots associated with data transmission over long distances.

The MSRR configuration is a set of position values of all modules, which completely determines the shape of the robot at any time. In this work, it is assumed that the target configuration is defined by a set of coordinates of the position of the geometric center of each module m_i. Thus, it is necessary to determine the target position q'_i of each module m_i in the required MSRR configuration $P = \{p_1, p_2, \dots, p_i\}$, where i - the number of robot modules. In this case, the path planning algorithm should operate in real time with the onboard resources of the MSRR modules.

B. Path planning when forming the configuration of MSRR

Consider the task of planning a path in the formation of an MSRR configuration using a swarm control strategy on a plane. The data that each module m_i transmits during the information exchange is the vector v_{m_i}, containing the coordinates of its own position, as well as the coordinates of the farthest robot located in the field of view of the module L:

$$v_{m_i} = \{q_i, q_j\} \quad (2)$$

Based on the data obtained, the distances between the module's own position and the position of the neighboring module, as well as between the module's own position and the coordinates of the farthest module located in the visibility range of the neighboring module are calculated:

$$\begin{cases} s_1 = \sqrt{(x_{q_i} - x_{q_j})^2 + (y_{q_i} - y_{q_j})^2}; \\ s_2 = \sqrt{(x_{q_L} - x_{q_i})^2 + (y_{q_L} - y_{q_i})^2}, \end{cases} \quad (3)$$

where s_1 is the distance between the modules m_i and the next module m_j, s_2 is the distance between the modules m_i and the farthest module located in the visibility zone L of the neighboring module m_j, whose position is indicated by q_L.

In case $s_2 > s_1$, then the farthest element in the visibility zone L of the module m_i becomes the module with coordinates (x_L, y_L), which is in view of L of the neighboring module m_j. The same data will be transmitted to the next elements at the next data transfer, and the coordinates of its own position are replaced by the coordinates of the neighboring module:

$$v_{m_i} = \begin{cases} \{q_j, q_L\}, if\ s_2 > s_1; \\ \{q_i, q_j\}, if\ s_2 < s_1. \end{cases} \quad (4)$$

Thus, after the n-th number of iterations, each robot of the group will know the positions of the modules most distant from each other, while the number of iterations does not depend on the number of MSRR modules. Accordingly, on the basis of these data, it is possible to determine the geometric center of the required MSRR configuration. For this, it is necessary to find the coordinates of the point O of the segment connecting the two modules farthest from each other:

$$x_O = \frac{x_{q_j} + x_{q_L}}{2}; \quad y_O = \frac{y_{q_j} + y_{q_L}}{2}. \quad (5)$$

Illustration of the definition of the geometric center of the MSRR configuration is presented in Figure 2.

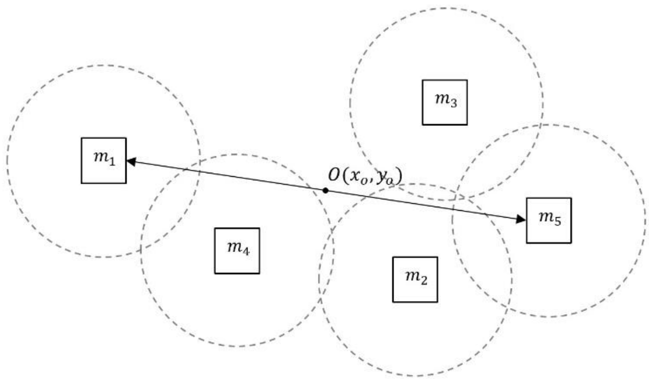

Fig. 2. Definition of the geometric center of the MSRR configuration

Having obtained the geometrical center of the configuration $O(x_O, y_O)$, it is necessary to calculate the generalized coordinates of the MSRR describing the position of each module m_i in the target configuration. To do this, it is necessary to find the vector $\overline{OP}$, which determines the distance between the calculated geometric centers of the configurations defined by $O(x_O, y_O)$ and the given $P(x, y)$:

$$\overline{OP} = (x_O - x;\ y_O - y). \quad (6)$$

After that, we can calculate the position of each point in the required configuration of the MSRR:

$$P' = \{p'_1 + \overline{OP},\ p'_2 + \overline{OP}, \dots, p'_i + \overline{OP}\}. \quad (7)$$

The main purpose of the development of the method is to reduce the time of formation of the MSRR configuration, so the criterion for choosing a position is the minimum distance from the current point q_i to the final one q'_i. Thus, it is necessary for each module m_i to determine the distance s'_i to each position p'_i and select the position p'_i of the MSRR configuration corresponding to the minimum distance:

$$\begin{cases} s'_i = \sqrt{(x_{q_i} - x_{p'_i})^2 + (y_{q_i} - y_{p'_i})^2}, \\ \forall\ p'_i \in P': (s'_i \le s'_{i-1} \Rightarrow p'_i = q'_i). \end{cases} \quad (7)$$

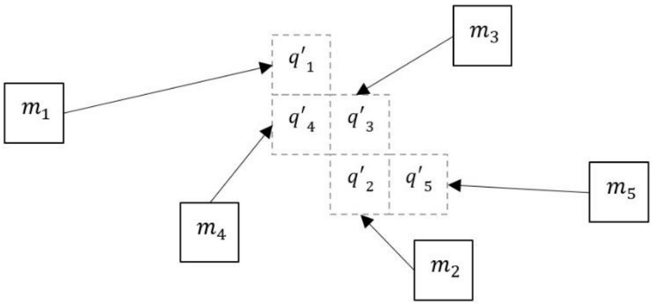

Fig. 3. Determining the position of the modules in the MSRR configuration

In the future, when moving to the target position of the module m_i, the vector v_{m_i} will be transmitted via the communication channel $c_{i,j}$, containing the current coordinates of the module q_i and the calculated coordinates of the target position q'_i:

$$v_{m_i} = \{q_i, q'_i\}. \quad (8)$$

IV. Results

In order to test the proposed method, a software implementation of the algorithm was made in the C# programming language. During the simulation, a computer with the following characteristics was used: Intel Core i7-8550U 1.8GHz processor, 8Gb RAM. The target configuration is defined by a set of coordinates of the center of each module.

The result of the simulation of the path planning with the formation of the MSRR configuration consisting of 5 modules using the developed method is presented in Figure 4.

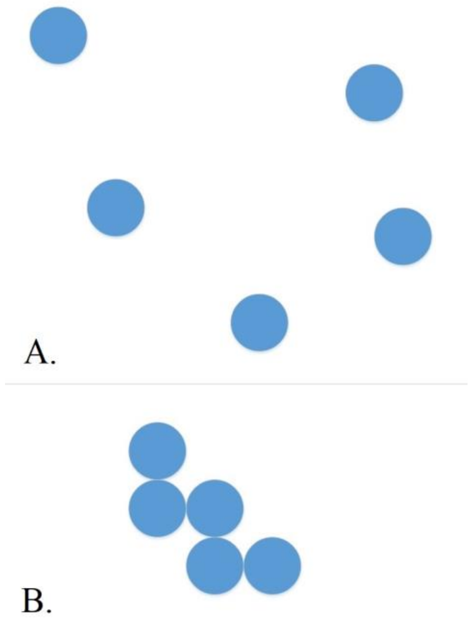

Fig. 4. Path planning with the formation of an MSRR configuration consisting of 5 modules. (*A - Initial Scene, B - The result of modeling*)

When modeling the work of the path planning algorithm, the execution time of the program was 30.99 ms. The advantage of the developed method is low computational complexity, which makes it possible to work in real time.

A series of experiments for MSRR consisting of 10, 25, and 50 modules was also carried out. The result of the path planning simulation for 50 modules is presented in Figure 5.

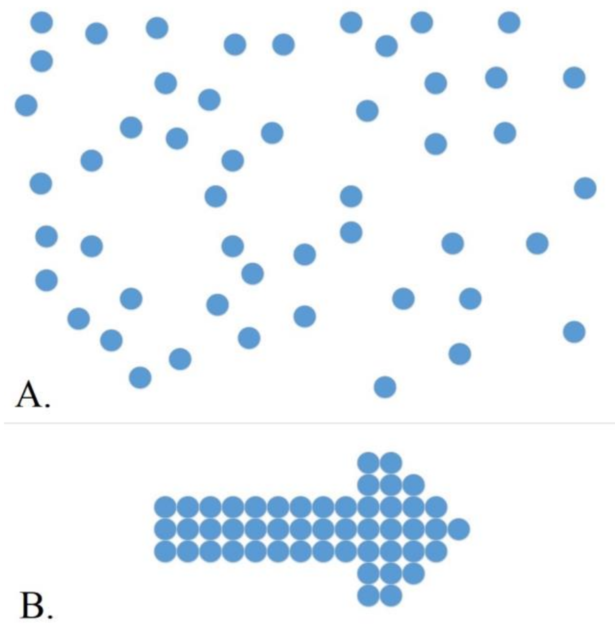

Fig. 5. The result of modeling the formation of the MSRR configuration. (*A - Initial Scene, B - The result of modeling*)

The dependence of the speed of the method on the number of the number of modules of the robot is presented in Table 1.

TABLE I. THE DEPENDENCE OF THE SPEED OF THE METHOD ON THE NUMBER OF MSRR MODULES

Number of MSRR modules	Time
5	34,8365 ms
10	59,8958 ms
25	98,3215 ms
50	212,4873 ms

Graphically, the dependence of the speed of the method is presented in Figure 6.

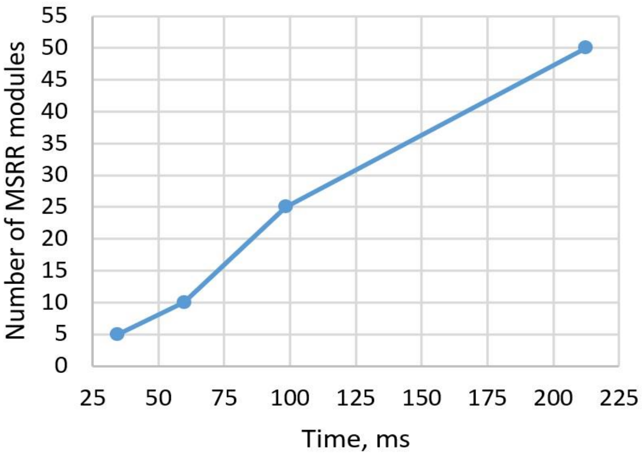

Fig. 6. Graph of the performance of the method on the number of modules

Based on the data presented in Table 1 and in Figure 6, it can be concluded that with an increase in the number of MSRR modules, the time required for program execution also increases linearly. It is also worth noting that the number of neighboring modules m_j, which transmit data over the communication channel $c_{i,j}$, also influences the path planning time.

Besides worth noting that the developed method can be applied not only to form the MSRR configuration, but also when managing a group of robots due to the possibility of system scalability and low computational complexity.

V. CONCLUSION

In the proposed method, only the final position of the module is calculated when forming the configuration without taking into account the orientation necessary to implement the coupling between the modules. This limitation is because the pairing mechanisms are different for each modular robot and it is necessary to consider this task for a particular robot. In addition, the method is applicable only for the formation of a configuration solely on the plane; to work in three-dimensional space, it is necessary to modernize the developed method. Further work is planned to study the above tasks.

Thus, this article presents a method for planning a path of travel when shaping a multifunctional modular robot configuration using a swarm control strategy. This approach allows real-time information exchange between robot modules and path planning is decentralized for each module, regardless of their number. The use of analytical geometry methods allows reducing the computational complexity of the method and avoiding the energy consumption of the onboard energy resources of the robot. The results of the simulation of the developed method for a robot consisting of 5-50 modules are presented, as well as the result of the research of the method performance on the number of robot modules.

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