Multiple mobile robots formation control using behavioral-based approach

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Abstract
This paper proposes a control strategy for a group of autonomous mobile robots to build a stable geometric formation. The main advantage of this approach is its high resistance to robot failures, which allows the formation to be maintained, as well as the absence of the need to predefine the connection graph between them.

Keywords
autonomous mobile robots, formation control, behavioral structure

1. Introduction

Modern trends in robotics development have made it possible to apply robotic systems in a wide range of practical tasks [1, 2]. At the same time, their production technology cost reduction, as well as the improvement of hardware and software components, has made it possible to use coordinated groups of autonomous mobile robots (AMRs) on a massive scale to solve such tasks. When organizing group control, particular attention is paid to achieving and maintaining a given geometric formation by the robots [3].

The currently existing approaches to building formations can be divided into three main categories [4]: "leader-follower", virtual structure, and behavioral approaches (behavioral structure). According to the first approach [5, 6], one or more leaders are chosen among the agents of the group, relative to which the other robots (followers) try to occupy the desired assigned position. Despite its high popularity, mainly due to its simplicity of implementation, this approach has a number of disadvantages. The main one is the low resistance to the failure of individual robots. Thus, if one of the leaders breaks down, the formation may split into independent groups that are unable to solve the task. In addition, it has a fairly high degree of centralization, since follower robots often do not have mechanisms for solving practical tasks, but only maintain a predetermined formation. These disadvantages are partially compensated for by using the virtual structure method [7, 8]. In this case, each robot is assigned to a virtual leader, a position in the formation that the robot must occupy. At the same time, the movement of the virtual formation can be set either centrally or decentrally during collective decision-making, or even, in rare cases, individually by each robot. Obviously, the decentralized option is of the greatest

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interest, but its application is associated with a significant increase in the computational load and communications within the group, which can be critical when robots solve a number of practical tasks.

This paper proposes an approach to formation building based on the behavioral structure method [9]. According to this approach, each robot adjusts its position relative to the current coordinates of the other group members, which ultimately allows the desired formation to be achieved. One of the main advantages of behavioral structure is the ability to organize independent control loops (behaviors) aimed at the parallel solution of several subtasks by robots. In addition, this approach allows for complete decentralization while maintaining the coordination of the entire group's actions. Currently, behavioral methods of formation organization are widely used in the work of scientists around the world [1, 10, 11]. However, many of them are designed in such a way that each robot is given a list of neighbors in advance, relative to which its position in the formation is determined. As in the case of the "leader-follower" approach, this can lead to incorrect formations in the event of the failure of several AMRs. The proposed control strategy eliminates this drawback.

2. Formation controll

The paper considers a strategy for controlling a group of AMRs, which are described by the following system of differential equations:

$$\begin{cases} \dot{q}_i(t) = v_i(t), \\ \dot{v}_i(t) = u_i(t), \end{cases} \\ i \in G, \|v_i\| \leq v_{\max}, \|u_i\| \leq u_{\max}, \tag{1}$$

where $q_i \in R^p$, $v_i \in R^p$, and $u_i \in R^p$ are the coordinate, velocity, and control vectors of the i-th robot; p is the dimension of the search space (in this work, $p = 2$ is assumed); v_{max} and u_{max} are the velocity and control constraints; G is the set of available AMRs. Let the velocity and control at the initial time ($t = 0$) be equal to zero, and the coordinates be randomly assigned in some neighborhood of a given point q_0.

According to the proposed approach, the control of each robot is specified by a linear combination of forces, which are responsible for individual behaviors.

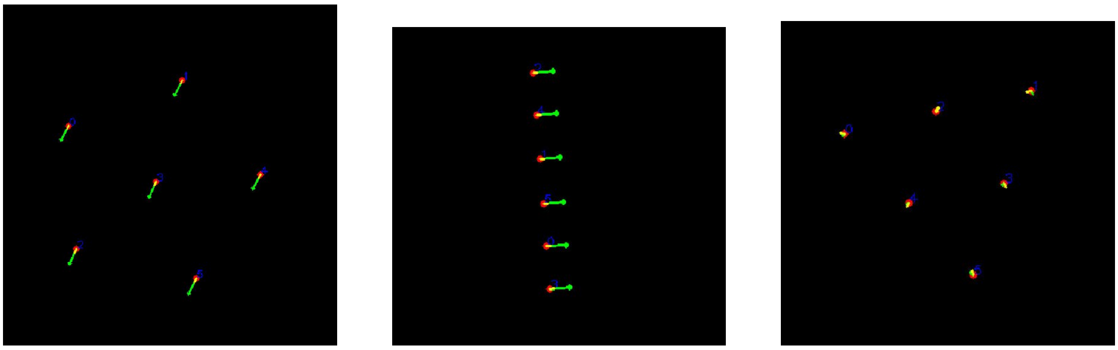
$$u_i = \sum_{k \in B} c_j F_i^k, \tag{2}$$

where $c_j \in R^+$ are controllable weight coefficients, B is the set of behaviors available to the robot.

The simplest formation that can be obtained is specified as follows:

$$F_i^f = -\sum_{j \in G} \left(\nabla_{q_i} U_{ij}^c \left(\|q_{ij}\| \right) \right), \quad i \neq j, \tag{3}$$

$$U_{ij}^c \left(\|q_{ij}\| \right) = \alpha \left(\frac{1}{2} \left(\|q_{ij}\| - d_{ij}^A \right)^2 + \beta \ln \|q_{ij}\| + \beta \frac{d_{ij}^A}{\|q_{ij}\|} \right), \tag{4}$$



(a) "Blob" formation (b) "Line" formation (c) "Triangle" formation

Figure 1: Visualization of the proposed formations.

where $q_{ij} = q_i - q_j$; ∇_{q_i} is the gradient with respect to the vector q_i; $d^A_{ij} > 0$ determines the desired distance between agents; $\alpha, \beta \in R^+$ are control parameters. Here, each robot tries to maintain a given distance from every other robot in the group, that leads to a circular formation. Its distinctive features are compactness and flexibility when robots pass through narrow areas.
The “line” formation is achieved through the use of a neighbor selection mechanic. Each AMR selects its neighborhood N_i, which includes one robot closest to the center of mass of the group and one in the opposite direction. At the same time, the second neighbor may be empty, which is typical for robots at the edges of the line. The function that determines this behavior is defined as:

$$F_i^f = a_1 \tan\left(\theta_i - \theta_{offset}\right) - a_2 \sum_{j \in N_i} \left(\nabla_{q_i} U^c_{ij}\left(\|q_{ij}\|\right)\right), \tag{5}$$

where θ_i is the angle between the main normal to the vector emanating from the robot to the center of mass of the group and the vector defining the desired movement direction; $a_1, a_2 \in R^+$ are control parameters. When $\theta_{offset} = 0$, the robots line up perpendicular to the desired movement direction, which can be obtained, for example, from other behaviors of the agent. Changing this parameter allows the group to be oriented at any angle to the movement vector. For example, when $\theta_{offset} = \pi/2$, the group is lined up in a column.

Another way to apply the neighbor selection mechanic is to organize a triangular formation. In this case, the two nearest AMRs in the direction of the center of mass of the group are selected as neighbors, and the agent’s behavior consists of two ideas: maintaining a given distance from neighbors and adjusting its position so that the angle θ between the vectors directed at the neighbors is equal to 600. Thus, the behavior for maintaining the formation is as follows:

$$F_i^f = a_3 \tan(\pi - 3\theta)(-1)^{\left[\frac{3\theta}{\pi}+1\right]} - a_4 \sum_{j \in N_i} \left(\nabla_{q_i} U^c_{ij}\left(\|q_{ij}\|\right)\right), \tag{6}$$

where $a_3, a_4 \in R^+$ are control parameters; [] is the operator for rounding to the nearest integer.

Examples of the above formations for a group of six AMRs are shown in Figure 1.

3. Conclusion

The proposed approaches to formation building based on the behavioral structure method have two important features. First, the control strategy is completely decentralized and does not require additional prior knowledge. Therefore, the failure of one or more robots does not lead to the loss of the formation, but causes its restructuring without involving additional calculations or planners. Second, the approach works correctly in the case of restrictions on the communication range, causing incomplete information about the coordinates of the group agents. Currently, work is underway to find behaviors for organizing a wider range of formations, as well as to develop a mechanism for individual decision-making on whether to change the formation during the task solution process, depending on its current conditions and environmental events.

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