DOI: 10.17587/mau.22.304-312

S. Yu. Kurochkin, kurochkin.smn@gmail.com, **A. A. Tachkov,** Cand. Sc., tachkov@bmstu.ru,
Science and Educational Center "Robotics" Bauman Moscow State Technical University,
Moscow, 105005, Russian Federation

Corresponding author: **Kurochkin S. Yu.,** Engineer of the Department "Automated transport systems",
Science and Educational Center "Robotics" Bauman Moscow State Technical, Postgraduate
of "Theory of Mechanisms and Machines" department of the Bauman, Moscow State Technical University University,
Moscow, 105005, Russian Federation, e-mail: *kurochkin.smn@gmail.com*

Accepted on March 5, 2021

Methods of Formation Control for a Group of Mobile Robots (a Review)

Abstract

The multi-robot formation control is an essential issue in robotics. This review focuses on important lines of research on current control issues and strategies on a group of unmanned autonomous vehicles/robots formation. In this paper, we provide a brief description of each method characterizing its key benefits and drawbacks. A multilayered classification of both centralized and decentralized formation control methods is proposed. We consider the classification of robot communication topologies in terms of centralized control. Seminal works dedicated to the practical application of centralized approach are briefly discussed. The majority of centralized methods are represented by a "leader-follower" approach, taking into account the robot's dynamics models. Furthermore, the most common models of vehicle dynamics are mentioned. In the framework of decentralized approach, behaviour-based algorithms, as well as swarm algorithms, are discussed. Then, we present an outlook of both centralized and decentralized virtual structure methods used in robot formation control. The described modifications of these methods allow tracing the evolution of the virtual structure approach to hybrid algorithms used for cooperative movement of a group of robots. This paper deals with formation control approach considering communication delays and low carrying capacity in an inter-vehicular communication network as very few works discussed this issue despite its relevance. We pointed out the main development trends of formation control approaches. The most effective approach is the integration of various methods of the formation control so that their disadvantages are nullified. As the same time, the most common disadvantage of discussed formation control methods is their weak conceptual framework in terms of kinematic and dynamic constraints of robots.

Keywords: *mobile robot, unmanned autonomous vehicle, formation control, formation navigation, leader-follower approach, behaviour-based approach, swarm intelligence, virtual structure approach*

For citation:

Kurochkin S. Yu., Tachkov A. A. Methods of Formation Control for a Group of Mobile Robots (a Review), *Mekhatronika, Avtomatizatsiya, Upravlenie,* 2021, vol. 22, no. 6, pp. 304—312.

DOI: 10.17587/mau.22.304-312

УДК 007.52, 004.75

DOI: 10.17587/mau.22.304-312

С. Ю. Курочкин, аспирант, kurochkin.smn@gmail.com,
А. А. Тачков, канд. техн. наук, начальник отдела
"Автоматизированные транспортные системы", tachkov@bmstu.ru,
НУЦ "Робототехника" МГТУ им. Н. Э. Баумана

Методы управления групповым движением мобильных роботов (обзор)

Управление согласованным движением группы мобильных роботов является одной из актуальных проблем современной робототехники. В настоящем обзоре представлены результаты анализа наиболее перспективных направлений исследований в данной области. Рассмотрены основные методы управления движением группы мобильных роботов с сохранением заданной геометрии строя. Представлено краткое описание каждого метода, показаны основные преимущества и недостатки. Предложена многоуровневая классификация методов управления движением, охватывающая как централизованные, так и децентрализованные методы. В рамках централизованного управления движением группы мобильных роботов рассмотрена классификация топологий организации связи между роботами, кратко описаны наиболее значимые работы, посвященные применению данного подхода на практике. Отмечено, что боль-

шинство централизованных методов реализуют подход «ведущий-ведомый». Рассмотрены алгоритмы, учитывающие при управлении строем динамику движения отдельных роботов, приведены наиболее распространенные динамические модели роботов. В рамках децентрализованного подхода к управлению согласованным движением групп роботов рассмотрены как коллективные, так и стайные алгоритмы управления. Представлен обзор класса методов на основе использования "виртуальной структуры", включающего как централизованные, так и децентрализованные методы управления согласованным движением группы роботов. Продемонстрирована эволюция данного подхода, рассмотрены его модификации, применяющиеся в гибридных алгоритмах управления согласованным движением группы. Рассмотрены работы, посвященные методам управления движением группы роботов с учетом возникающих в каналах связи запаздываний, а также ограниченной пропускной способности, указана недостаточная проработанность данных методов. В работе показаны основные тенденции развития методов группового движения роботов. Отмечено, что наиболее перспективным является комбинирование различных алгоритмов группового управления, что позволяет нивелировать недостатки, возникающие при использовании их по отдельности. Показано, что наиболее распространенным недостатком существующих методов управления является недостаточная проработка алгоритмов управления группой мобильных роботов с точки зрения учета кинематических ограничений роботов, а также их динамики.

Ключевые слова: *мобильный робот, безэкипажное транспортное средство, управление строем, навигация строя, подход "ведущий-ведомый", поведенческий подход, роевой интеллект, метод виртуальной структуры*

1. Introduction

An application of multi-robot systems covers a wide range of applied problems for both civil [1—3] and military purposes [4—6], while the number of robots in a group can reach several hundred units [7]. One of the most urgent scientific problems of group robotics today is the problem of coordinated motion control of mobile robots with their maintenance of the formation geometry. For example, in [8, 9] a formation control is considered when transporting passengers and goods indoor as well as on public roads and over rough terrain [10]. The most of papers dealing with public transportation are related to CACC — Cooperative Adaptive Cruise Control [11, 12]. In the CACC system, autonomous vehicles [13] are combined into a platoon and drive at the same speed, maintaining the desired shape or formation geometry communicating over the wireless network [1].

An impressive number of articles are devoted to the problem of motion control for mobile robot group while maintaining their formation. For example, the query "robot formation control" in Google Scholar search engine is produced more than 838,000 results. In the last five years alone, the number of articles is devoted to the coordinated control of the robotic group movement is about 64,000. To determine the trends in the design of group motion control methods over the past quarter of a century, the authors of this paper have summarized the disparate results of researches in this area and have proposed a multi-level classification based on the "strategy for controlling a group of robots".

The remaining part of this paper is organized as follows. In Section 2, a proposed classification of methods for the formation control is presented. Section 3 is devoted to reviewing all the main methods based on a leader-follower approach. In Section 4, we consider methods of motion control for a mobile robot group are most often implemented by reactive, or "behavioural" algorithms are known as a behaviour-based approach. In Section 5, methods based upon a virtual structure approach are discussed. Finally, conclusions are made in Section 6.

2. Proposed classification of methods and approaches used for formation control

In this section, we introduce the proposed by the authors' classification of methods used for formation control shown in Fig. 1.

The most frequent formation control methods are divided into three classes: leader-follower methods (the centralized control strategy), behavioural methods (the decentralized control strategy) and virtual structure methods, which can be both centralized and decentralized.

Centralized strategies are suggested a robot group is controlled by the so-called Central Control Unit (CCU), which plans robot paths and assigns tasks for each robot individually [14]. The robot group can also assign a leader robot (static or dynamic) which tracks a predefined path, while the others act as followers and track the leader according to their states. The main advantage of this method consists of the relative simplicity of robots-followers and used control algo-

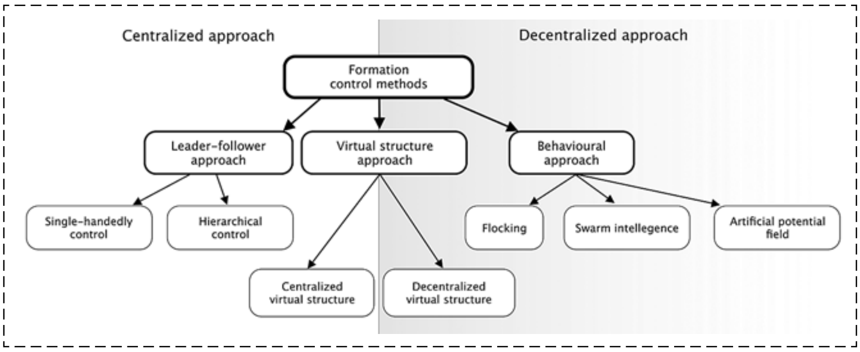

Fig. 1. Classification of methods for the formation control

rithms. The behaviour of robots can be analyzed using standard methods of the control theory. The disadvantages of leader-follower methods can be attributed to the fact that the error of the leader or the control center punishes the whole group and often leads to not-mission capable for further execution [15].

The methods relating to the decentralized approach include methods based on imitation of the animal behaviour, the so-called "behavioural" or "reactive" approaches [16]. For the first time, such a reactive approach was described by Craig Reynolds in 1987 [17]. In this method, each agent of the group has a pre-programmed set of behaviours which it chooses scenario-depended: the state of the environment, the behaviours of the other agents.

As an advantage of this class of methods, we can note their convenience for robots performing tasks in a dynamically changing environment and with moderate interaction between robots [15].

In the class of virtual structure methods, the desired position of each robot within the given structure and the shape of formation are specified. Thus, each robot is assigned its virtual leader and it has to minimize the error between its current and the desired position in the formation. It's important to stress that the path of the formation is only set to the entire virtual structure and not for each robot individually. This class includes both centralized and decentralized methods. Centralized virtual structure implies that positions of the robots are observed by CCU, which adjusts robot behaviour and appoints their poses in the formation. While using a decentralized approach, robots exchanging information, distribute their positions in formations they are involved.

The advantage of this class of methods, first of all, is the simplicity of setting the coordinated movement of the group, which is required, for example, when carrying bulky cargo. The disadvantages include the need to plan the path for the entire structure and when bypassing both static and dynamic obstacles, as a result of which the trajectories of individual robots may not be optimal [15].

3. Leader-follower approach

According to the centralized strategy, a mobile robot group is considered by a hierarchical structure. There is either a CCU or a leading robot at the top level of this structure.

Leader robots can be assigned in the group according to the number of robots and their homogeneity. Typically, a robot-follower equipped with a smaller set of navigation sensors than the leader. The information exchange between robots is organized following one of the communication topologies, an overview of them is given in [18]. The most commonly used communication topologies are presented in Fig. 2.

In many situations, the leader-follower approach is mostly used to control vehicle platoons on the highway [19—23] or on the varying terrain [24, 25]. For example, Öncü et al. [19] consider the Cooperative Adaptive Cruise Control (CACC) system, which controls a group of vehicles of the same type driving along the highway. Communication between vehicles is organized according to the principle of a bidirectional topology (Fig. 2 c); a wireless communication channel with transport delays and limited bandwidth is used for data exchange. These communication limitations were considered by authors during the development of a control system for a group of vehicles movement [19]. The described system made it possible to ensure the reliable control of a vehicle platoon with an interval between cars of 20 m and a speed of 65 km/h with communication delays less than 750 ms.

The stability of the proposed method was analyzed in terms of string stability methods. The studied parameters were the transport delay in the communication channel, the number of cars in the group and the size of intervals between vehicles in the column. In the formation control system, as well as in the numerical simulation of the formation movement, a third-order dynamic car model was used (1) taking into account the delay in the wheel drive control loop:

$$\begin{cases} \dot{r}_i = v_i(t); \\ \dot{v}_i = a_i(t); \\ \dot{a}_i = \dfrac{1}{T_i} a_i(t) + \dfrac{1}{T_i} u_i(t - \tau_{a,i}), \end{cases} \tag{1}$$

where r_i, v_i, a_i — the absolute position, the velocity and the acceleration of the i-th vehicle, respectively; T_i — the parameter characterizing the internal actuator dynamics; u_i — the acceleration for the i-th vehicle; $\tau_{a,i}$ — the constant actuation delay.

The effectiveness of the proposed algorithm was shown in [20], where the problem of forming a platoon and its further safe movement at a speed of 100 km/h in the presence of a transport delay up to 0.15 s has been solved.

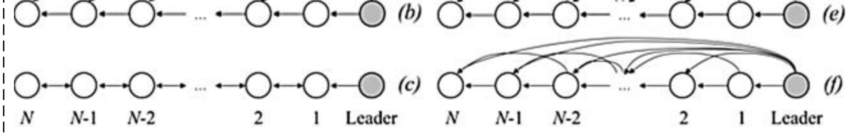

Fig. 2. Leader-follower topologies:
a — predecessor following topology; *b* — predecessor-leader following topology; *c* — bidirectional topology; *d* — bidirectional-leader topology; *e* — two-predecessor following topology; *f* — two-predecessor-leader following topology

The method of formation control of non-identical vehicles while exchanging information over a wireless network of the IEEE 802.11p standard was proposed in [20]. This study was also taken into account transport delay in the communication network, packet loss as well as the switching time between different communication topologies (Fig. 2 a—f). In the in-line simulation in the Plexe simulator [21], the third-order linear model [22] similar to (1) was used. The stability of the control system for group motion was analyzed via Lyapunov-Razumikhin and Lyapunov-Krasovskii theorems. The transport lag margin in the communication channel was determined using the methods of linear matrix inequalities [20, 23].

It is widely known that the formation control of various shapes (diamond, chain, double column, etc.) is still a fundamental problem in unmanned vehicles. A detailed review of the control method in the formation of the "convoy" moving in a 2D-plane is presented in [24]. The navigation method for a group of heterogeneous mobile autonomous robots using the rules of the nearest neighbour was presented in [25]. The essence of this method is that robots of the group planning their trajectories taking into account the positions of their neighbours. The leader of such group moves along a planned trajectory and all other robots repeat his path with a given displacement [25, 24]. Further, this control method includes a mechanism for the reconfiguration of the formation, which is designed to avoid obstacles.

In general, the leader-follower approach can be used in sub-tasks of the group's motion control. For example, the leader-follower approach was used for the coordinated group's formation control while changing the formation shape [26]. In the control system [26], a-priori defined robot-leader sends commands to the rest of the group. The robots-followers move to their desired positions while avoiding collisions with obstacles and other robots, if the robot-follower finds its neighbour, then it moves after the neighbour until this robot-leader is in the desired position. In addition, the Hungarian algorithm was used in [26] to solve the problem of he minimizing the cost of moving by robots.

4. Behaviour-based approach

Decentralized methods of motion control of the robot group are most often implemented by reactive, or "behavioural" algorithms. These algorithms are based on the imitation of behavioural reactions of various organisms common in the living nature. Such algorithms are based on the concept of using competencies (behaviours) in known situations. Based on the information received from the robot's sensors, its control system selects the most appropriate behaviour for the environment. The basic principles of the behavioural approach are described in [27]:

— the behaviours of each robot are represented by standard algorithms implemented both at the software and hardware levels built with separate modules;

— each behaviour receives input information from the robot's sensors (radars, tactile sensors, lidars or cameras) and/or from other modules of its control system, and can also send commands to the robot's actuators and/or other modules of the robot's control system;

— the behaviours can independently receive data from the same sensors and send commands to the same actuators;

— the behaviours are relatively simple software modules added to the control system sequentially;

— the behaviours are performed in parallel taking into account interaction dynamics among behaviours and between behaviours and the environment.

The behavioural-based methods are used for control of a robot group while motioning in the formation of a certain geometric shape (pattern). For example, in [10], the problem of a moving convoy over rough terrain is considered. Using behavioural-based methods, the logic of movement of individual robots included in the group is implemented by simple behaviours: a movement to the target point, avoiding collisions with obstacles and other robots, a maintaining the shape of the formation (column, line, diamond and wedge). Two variants of the formation organization were also considered: relative to the geometric center and relative to the leading robot. As the experiments have shown, the formation relative to the leading robot is best suited for tasks where a column of robots is led by a human who independently navigates the terrain and drive around various obstacles. It was also noted that in this approach, the loss of communication or breakdown of one of the robots does not affect the overall behaviour of the system. The method of forming a group relative to its geometric center, as the authors note, has better performance [10], but the failure of one of the robots can stop the movement of the whole group. It is also noted that in the version of movement with the leader, the load on the communication network is reduced since there is no need for all robots to participate in the exchange of location information: only the leader transmits his position, and the necessary positions of the other robots of the group are calculated relative to him.

As another example describing the principle of operation of the behavioural approach, we can cite the robot motion control system described in the article [28]. In this paper, the behavioural-based method is used to control a group of robots, which task was to move the box in a dynamically changing environment. The control algorithm describes four possible situations in which robots may find its way into the process of performing a given task, using two parameters: the complexity of the task and the number of active robots. The architecture of the behaviour

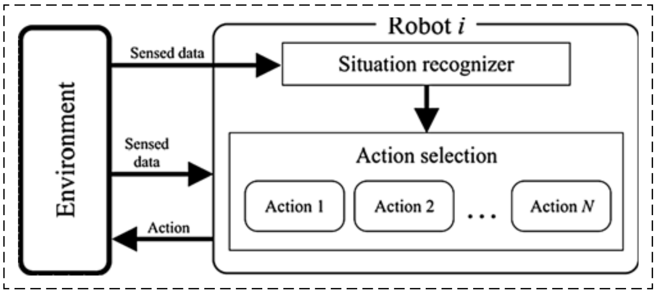

Fig. 3. The architecture of behaviour actions selection algorithm

actions selection algorithm of each robot is schematically shown in Fig. 3. Each robot recognizes one of the four possible situations and chooses the appropriate action for it. Thus, robots act according to the principles of a behavioural approach, responding to changes in the environment and adaptively selecting actions that correspond to the current situation.

A key node in this control system using a behavioural approach is a coordination system that links the available responses and output of the robot's actuators. The following coordination methods are usually used: an arbitration or a mixed strategy. When the arbitration method is used, only one of the available behaviours can participate in the computation of the control signal. This method is simple to implement, but unstable [29]. It is also noted that the choice of the correct rule (behaviour) is a non-trivial task [29]. In the mixed strategy method, all behaviours are simultaneously involved in the computation of the control signal, but the contribution of each is proportional to its applicability (weight) for the current situation. One of the implementations of the method with mixed strategy considered in the article [30] is presented in Fig. 4.

In such a control system, there is a supervisor unit that, based on data from the robot's sensors, tunes the weight for a set of actions, which are then added up and the resulting action is applied to the lower level of the robot's control system.

A modification of the behavioural approach called NSB-control (Null-Space-based Behavioral Control) was proposed in [31, 32]. In the proposed control system there is a supervisor unit that assigns a certain weight to each action based on the robot's sensor data. In other words, each pre-described behaviour is assigned a priority, so that the robot can perform several actions simultaneously. Low-priority behaviours are not executed if they conflict with high-priority behaviours. Using this method, algorithms for the movement of robots in the formation of a certain geometric shape, the tasks of escorting a moving object, the movement of a flock, and patrolling a certain area were implemented in [31]. A detailed review of these algorithms is presented in the article [32]. The behavioural-based approach is also used in works devoted to the transportation of large-sized cargo by a group of UAVs, where the same problem of maintaining a certain form of structure is solving [33—35].

An algorithm using the principles of platoon movement is proposed in [36]. To maintain the formation of a certain geometric shape, the method of potentials was applied. Using simulation, it was shown that the proposed algorithm ensures the movement of a robot group in the formation of a given shape, while the same speed of movement of robots is provided during the movement. A similar approach was applied in the article [37], which describes the method of controlling a group of non-holonomic robots moving along a straight road. A safe distance between robots and maintaining the shape of the system was provided using the method of potentials. The LaSalle invariance principle was applied to analyze the stability of the robot's formation control system [38]

Another category of behavioural methods which used for controlling the movement of groups of robots is the swarm intelligence methods. Swarm intelligence methods are usually taken as an approach to managing and optimizing distributed systems using stable, decentralized, self-organizing methods based on the behaviour of social insects [39]. This category of methods of group motion control is well-known ant algorithms, a pack of wolves, swarm of bees, etc. Some of the most popular algorithms [40], as well as examples of their application, are shown in Table.

A detailed description of the above algorithms is given in the monograph [55]. In the [56], the algorithm of an ant colony optimization (ACO) was applied to solve the problem of rearrangement a group of robots in order to reduce the distances travelled by each robot in the process of changing the formation shape. Also, the ACO algorithm was used in the problem of forming a group of robots into the formation of a given shape. In [57], ants and the pheromones that they emit were implemented as mobile software agents. The diagram of the algorithm is shown in Fig. 5.

One agent, called the ant, controls the robot's actions, and another agent, called the pheromone, tells the ant agent

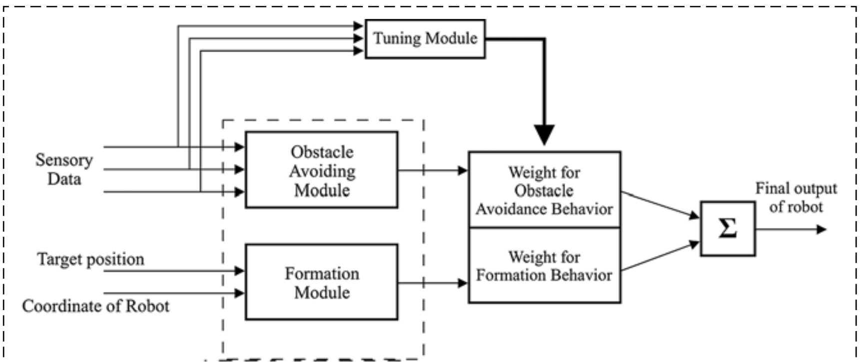

Fig. 4. Architecture of the control system for multi-robot formation control

Algorithms inspired by swarm intelligence

Algorithm	Algorithm details	Algorithm survey
Particle Swarm Optimization (PSO)	[41], [42]	[43], [44]
Ant Colony Optimization (ACO)	[45]	[46]
Artificial Bees Colony Optimization (ABCO)	[47]	[48]
Bacteria Foraging Optimization (BFO)	[49]	[50]
Glowworm Swarm Optimization (GSO)	[51]	[52]
Grey Wolf Optimizer (GWO)	[53]	[54]

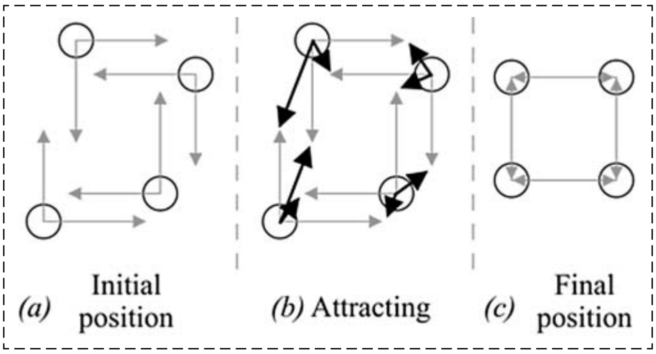

Fig. 5. The process of forming a shape by the group of ant agents

in which direction the robot is moved. Each ant agent knows only a fraction of the information about the shape of the formation. In order to spread partially known information among its neighbours, each ant agent generates pheromone agents and sends them to the surrounding robots (Fig. 5 a). The sent pheromone agent searches for the ant agent to which it was directed, and when the pheromone finds it, the ant agent leads the robot by following the pheromone agent's instructions, thus forming a building element (Fig. 5 b).

To solve the problem of a robot's rearrangement in the group, the known bat algorithm is also used. In [58], this algorithm was used to find the time-optimal method of group rearrangement. The algorithm has shown high efficiency in controlling a group of robots described by inaccurate mathematical models, in comparison with the CPTD (control parameterization and time discretization) method [59] and "line of sight" [60].

5. Virtual structure approach

The concept of the virtual structure was first introduced in [61] for methods of coordinated motion control of robot groups. In [61], a movement of three robots in shape formation of a triangle was described. The idea of the proposed method was to make similar the shapes of formation to a rigid formation, which elements are always at a fixed distance from each other, due to a system of physical constraints.

In a similar system, the perturbation of one element extends to all the others. An important feature of this class of methods is that if one of the robots cannot continue moving, for example, in the event of a breakdown, then the other robots do not allow the formation to break up until some high-level control process detects the failure and decides on further actions (Fig. 6). Among the advantages of the virtual structure method in comparison with the leader-follower approach, it is noted:

— a leader robot does not require due to high fault tolerance appointment of a group;

— the method of virtual structure can implement the movement of a robot group–in the formation of any possible shape;

— the virtual structure method does not require high computational burden for each robot in a centralized approach;

— there are no complex protocols for communication and decision-making.

According to the paper [61], the proposed method can be used in problems that require coordinated movement of robot groups transporting large objects, for example, boxes. This method can also be used in problems related to laser interferometry, in which it is required that several objects move in space, maintaining a fixed geometry with an accuracy of 1 cm [62].

In [62], the main directions of development of the proposed virtual structure algorithm were identified: the use of flexible or deformable structures, as well as hierarchical virtual structures. In [63], the virtual structure method was proposed for controlling robot groups moving along several lanes of the highway while maintaining the formation of a given shape. To achieve that, the control problem was divided into two subtasks: a high-level one for controlling the formation using the virtual structure method, and a low-level one for trajectory control of the robot's movement using a predictive model. The proposed method provided both the movement of robots in

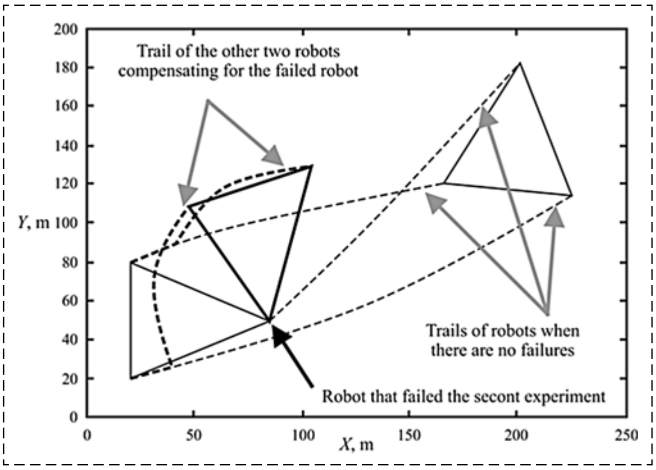

Fig. 6. The trajectory of three robots with a robot failure

the formation of a given shape and the prevention of collisions between robots. In [64] was proposed the architecture of an adaptive management system to arrange robots using a virtual structure, and the control system for the motion of a group of nonholonomic robots with reconfigurable formation shape was developed. Two controllers were used, the first one provided stable control of the group during a change in the configuration of the formation, and the second one controlling the movement of robots relative to a given position in the formation.

Among the works devoted to methods of controlling the formation of robots using flexible virtual structures, one can note the article [65]. The control system for a robot group is used three control algorithms: an algorithm for maintaining the shape of the system and avoiding collisions between robots, an attraction algorithm that ensures convergence to a given shape of the system, and an algorithm for avoiding obstacles. The stability of the proposed control system to external disturbances using the Lyapunov method was studied in [66]. The flexible virtual structure was described as a system of masses, springs, and dampers connecting each robot to its neighbours. The proposed method allowed a group of robots to behave like a flexible body, which can be used to avoid obstacles.

In [67], the architecture of a distributed control system for the motion of a robot group in an unstructured environment was considered. The architecture has used as a combination of a behavioural approach and a virtual structure method that, as the authors note [67], has the advantages of both control methods. The robot motion control system includes two algorithms: an algorithm for maintaining the shape of the system (a robot moves to its place in a virtual structure) and an algorithm for avoiding obstacles (Fig. 7). The robot control system based on the robot's sensors data selects the optimal algorithm for the current situation, like a supervisor using the arbitration method in a behavioural approach.

In subsequent works [68, 69], the authors proposed a modification of the control system for a group of unmanned vehicles: Multi-Layer and Multi-Controller (MLMC) architecture for dynamic navigation in the formation of a UGV's group in constrained environments. This control method also consists of two approach combination: the centralized leader-follower based approach and the decentralized behavioural-based approach, i.e. hybrid (centralized/decentralized) control as well as cognitive/reactive. The centralized part of the control algorithm is used to solve global tasks performed by the group, and the decentralized part is responsible for the navigation of robots and their local tasks, such as avoiding obstacles. In a group of robots controlled by this system, there is a leader leading the entire group and planning the path to avoid obstacles, taking into account the kinematic limitations of the other robots in the group. Also, these restrictions are used by the group control system during shape formation reconfigurations. In [70], the stability of the described control system is analyzed during the movement of a triangular structure in a circle with a change in the direction of movement using the Lyapunov method.

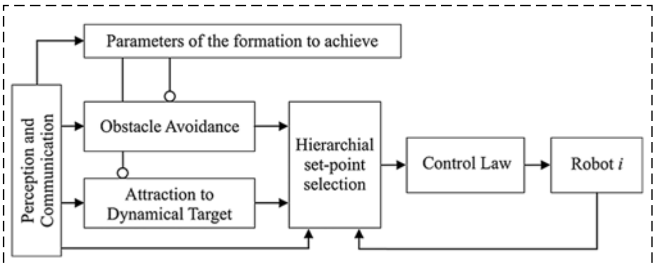

Fig. 7. Architecture of multi-robot formation control using hybrid control (deliberative/reactive)

6. Conclusion

In this paper, we presented a literature review on the current research efforts on formation control for a group of robots/vehicles. Some well-developed control methodologies have been introduced. Over the last quarter of a century, there has been a tendency towards combination of different group motion control algorithms in order to eliminate the disadvantages that arise when using them separately. The problem of controlling the movement of a formation of robots does not lose its relevance, while the most promising methods for controlling a group of robots are hybrid methods that combine elements of both centralized and decentralized system.

In our opinion, the most promising methods are based on combinations of different approaches, especially those that use the virtual structure method as part of the multi-controller architecture. It is important to note the high versatility of the latter method, its low computational burden, as well as the low communication network load. It is also possible to use a decentralized virtual structure in hybrid control methods for a group of robots.

When developing the described control systems for groups of mobile robots, the authors usually follow only the kinematic constraints of mobile robots, with the exception of methods related to group movement on a one-lane road or highway in which dynamic models of second-and third-order vehicles are used. Also, only in a few of the reviewed works, the authors take into account the limitations imposed by the communication system (delays and bandwidth limitations). These shortcomings are present in most of the described works, from which it can be concluded that a thorough study of these problems is required.

References

1. **Kavathekar P., Chen Y. Q.** Vehicle platooning: A brief survey and categorization, *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, 2011, pp. 829—845.
2. **Alonso-Mora J., Baker S., Rus D.** Multi-robot formation control and object transport in dynamic environments via constrained optimization, *The International Journal of Robotics Research*, 2017, vol. 36, no. 9, pp. 1000—1021.
3. **Das B., Subudhi B., Pati B. B.** Cooperative formation control of autonomous underwater vehicles: An overview, *International Journal of Automation and computing*, 2016, vol. 13, no. 3, pp. 199—225.
4. **Rudianov N. A., Khrushchev V. S.** Substantiation of the appearance of combat and support robotic complexes of the Ground Forces, *Engineering journal: science and innovations*, 2013, no. 8 (in Russian).
5. **Young S., Kott A.** Control of small robot squads in complex adversarial environments: A review. ARMY RESEARCH LAB ADELPHI MD, 2009.
6. **Scharre P.** Robotics on the battlefield part II, Center for New American Security, 2014.
7. **Chartier C., Swarming N. E.** C4ISR, and US Military Transformation, *Proc. of Conf. on Swarming: Network Enabled C4ISR*, 2003.
8. **Dey K. C. et al.** A review of communication, driver characteristics, and controls aspects of cooperative adaptive cruise control (CACC), *IEEE Transactions on Intelligent Transportation Systems*, 2015, vol. 17, no. 2, pp. 491—509.
9. **Alonso-Mora J. et al.** Reactive mission and motion planning with deadlock resolution avoiding dynamic obstacles, *Autonomous Robots*, 2018, vol. 42, no. 4, pp. 801—824.
10. **Balch T., Arkin R. C.** Behavior-based formation control for multirobot teams, *IEEE transactions on robotics and automation*, 1998, vol. 14, no. 6, pp. 926—939.
11. **Sheikholeslam S., Desoer C. A.** Longitudinal control of a platoon of vehicles, *1990 American control conference,* IEEE, 1990, pp. 291—296.
12. **Girard A. R. et al.** A control architecture for integrated cooperative cruise control and collision warning systems, *Proceedings of the 40th IEEE Conference on Decision and Control (Cat. No. 01CH37228),* IEEE, 2001, vol. 2, pp. 1491—1496.
13. **SAE On-Road** Automated Vehicle Standards Committee. Taxonomy and definitions for terms related to driving automation systems for on-road motor vehicles, *SAE International*, (J3016), 2016.
14. **Kalyaev I. A., Gaiduk A. R., Kapustyan S. G.** Models and algorithms of collective control in groups of robots, Moscow, FIZMATLIT, 2009, 280 p. (in Russian).
15. **Hirsch M. et al.** Optimization and Cooperative Control Strategies, *Proceedings of the 8th International Conference on Cooperative Control and Optimization,* Springer Science & Business Media, 2009, vol. 381.
16. **Beloglazov D. A. et al.** Group control of mobile objects in uncertain environments, Moscow, Fizmatlit, 2015 (in Russian).
17. **Reynolds C. W.** Flocks, herds and schools: A distributed behavioral model, *Proceedings of the 14th annual conference on Computer graphics and interactive techniques*, 1987, pp. 25—34.
18. **Li S. E. et al.** An overview of vehicular platoon control under the four-component framework, *2015 IEEE Intelligent Vehicles Symposium (IV),* IEEE, 2015, pp. 286—291.
19. **Öncü S. et al.** Cooperative adaptive cruise control: Network-aware analysis of string stability, *IEEE Transactions on Intelligent Transportation Systems*, 2014, vol. 15, no. 4, pp. 1527—1537.
20. **Salvi A., Santini S., Valente A. S.** Design, analysis and performance evaluation of a third order distributed protocol for platooning in the presence of time-varying delays and switching topologies, *Transportation Research Part C: Emerging Technologies*, 2017, vol. 80, pp. 360—383.
21. **Segata M. et al.** Plexe: A platooning extension for Veins, *2014 IEEE Vehicular Networking Conference (VNC)*, IEEE, 2014, pp. 53—60.
22. **Rajamani R.** Vehicle Dynamics and Control. Springer, Boston, MA, 2012.
23. **Santini S. et al.** A consensus-based approach for platooning with intervehicular communications and its validation in realistic scenarios, *IEEE Transactions on Vehicular Technology*, 2016, vol. 66, no. 3, pp. 1985—1999.
24. **Das A. K. et al.** A vision-based formation control framework, *IEEE transactions on robotics and automation*, 2002, vol. 18, no. 5, pp. 813—825.
25. **Zhu Hua.** Motion control of a group of mobile robots in a "convoy" type formation. BMSTU, Moscow, 2018 (in Russian).
26. **Wan S., Lu J., Fan P.** Semi-centralized control for multi robot formation, *2017 2nd International Conference on Robotics and Automation Engineering (ICRAE),* IEEE, 2017, pp. 31—36.
27. **Siciliano B., Khatib O.** Springer handbook of robotics, Springer, 2016.
28. **Yamada S., Saito J.** Adaptive action selection without explicit communication for multirobot box-pushing, *IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews),* 2001, vol. 31, no. 3, pp. 398—404.
29. **Egerstedt M.** Behavior based robotics using hybrid automata, *International Workshop on Hybrid Systems: Computation and Control*, Springer, Berlin, Heidelberg, 2000, pp. 103—116.
30. **Dong J., Chen H. T., Liu S.** A behavior-based policy for multirobot formation control, *Applied Mechanics and Materials. Trans Tech Publications Ltd*, 2012, vol. 220, pp. 1181—1185.
31. **Antonelli G.** et al. Experiences of formation control of multi-robot systems with the Null-Space-based Behavioral Control //Proceedings 2007 IEEE international conference on robotics and automation. IEEE, 2007, P. 1068—1073.
32. **Antonelli G., Arrichiello F., Chiaverini S.** The NSB control: a behavior-based approach for multi-robot systems, *Paladyn, Journal of Behavioral Robotics*, 2010, vol. 1, no. 1, pp. 48—56.
33. **Antonelli G.** et al. CAVIS: a Control software Architecture for cooperative multi-unmanned aerial VehIcle-manipulator System, *IFAC Proceedings Volumes*, 2014, vol. 47, no. 3, pp. 1108—1113.
34. **Baizid K.** et al. Behavioral control of unmanned aerial vehicle manipulator systems, *Autonomous Robots*, 2017, vol. 41, no. 5, pp. 1203—1220.
35. **Muscio G.** et al. Coordinated control of aerial robotic manipulators: theory and experiments, *IEEE Transactions on Control Systems Technology*, 2017, vol. 26, no. 4, pp. 1406—1413.
36. **Lei B., Li W.** Formation control for multi-robots based on flocking algorithm, *International Conference on Intelligent Robotics and Applications*, Springer, Berlin, Heidelberg, 2008, pp. 1238—1247.
37. **Hayashi Y., Namerikawa T.** Flocking algorithm for multiple nonholonomic cars, *2016 55th Annual Conference of the Society of Instrument and Control Engineers of Japan (SICE)*, IEEE, 2016, pp. 1660—1665.
38. **La Salle J. P.** The stability of dynamical systems, Society for Industrial and Applied Mathematics, 1976.
39. **Bonabeau E. et al.** Swarm intelligence: from natural to artificial systems, Oxford university press, 1999, no. 1.
40. **Soni A., Hu H.** Formation control for a fleet of autonomous ground vehicles: A survey, Robotics, 2018, vol. 7, no. 4. pp. 67.
41. **Kennedy J., Eberhart R.** Particle swarm optimization, *Proceedings of ICNN'95-International Conference on Neural Networks*. IEEE, 1995, vol. 4, pp. 1942—1948.
42. **Shi Y., Eberhart R.** A modified particle swarm optimizer, *1998 IEEE international conference on evolutionary computation pro-*

ceedings. IEEE world congress on computational intelligence. IEEE, 1998, pp. 69—73.

43. **Sengupta S., Basak S., Peters R. A.** Particle Swarm Optimization: A survey of historical and recent developments with hybridization perspectives, *Machine Learning and Knowledge Extraction*, 2019, vol. 1, no. 1, pp. 157—191.

44. **Poli R., Kennedy J., Blackwell T.** Particle swarm optimization, *Swarm intelligence*, 2007, vol. 1, no. 1, pp. 33—57.

45. **Dorigo M., Caro G. D., Gambardella L. M.** Ant algorithms for discrete optimization, *Artificial life*, 1999, vol. 5, no. 2, pp. 137—172.

46. **Mohan B. C., Baskaran R.** A survey: Ant Colony Optimization based recent research and implementation on several engineering domain, *Expert Systems with Applications*, 2012, vol. 39, no. 4, pp. 4618—4627.

47. **Karaboga D., Basturk B.** A powerful and efficient algorithm for numerical function optimization: artificial bee colony (ABC) algorithm, *Journal of global optimization*, 2007, vol. 39, no. 3, pp. 459—471.

48. **Karaboga D. et al.** A comprehensive survey: artificial bee colony (ABC algorithm and applications, *Artificial Intelligence Review*, 2014, no. 1, pp. 21—57.

49. **Passino K. M.** Biomimicry of bacterial foraging for distributed optimization and control, *IEEE control systems magazine*, 2002, no. 3, pp. 52—67.

50. **Rani B. S., Kumar C. A.** A comprehensive review on bacteria foraging optimization technique, *Multi-objective Swarm Intelligence,* Springer, Berlin, Heidelberg, 2015, pp. 1—25.

51. **Krishnanand K. N., Ghose D.** Detection of multiple source locations using a glowworm metaphor with applications to collective robotics, *Proceedings 2005 IEEE Swarm Intelligence Symposium, 2005. SIS 2005.* IEEE, 2005, pp. 84—91.

52. **Karegowda A. G., Prasad M.** A survey of applications of glowworm swarm optimization algorithm, *International journal of computer applications*, 2013, vol. 975, pp. 39—42.

53. **Mirjalili S., Mirjalili S. M., Lewis A.** Grey wolf optimizer, *Advances in engineering software*, 2014, vol. 69, pp. 46—61.

54. **Faris H. et al.** Grey wolf optimizer: a review of recent variants and applications, *Neural computing and applications*, 2018, vol. 30, no. 2, pp. 413—435.

55. **Karpenko A. P.** Modern algorithms for search engine optimization. Algorithms inspired by nature, Moscow, BMSTU, 2014 (in Russian).

56. **Yang L., Gongyou T., Peidong W.** Formation distance problem in multi-agents control, *2012 Fifth International Conference on Intelligent Computation Technology and Automation*, IEEE, 2012, pp. 181—184.

57. **Oikawa R., Takimoto M., Kambayashi Y.** Distributed formation control for swarm robots using mobile agents, *2015 IEEE 10th Jubilee International Symposium on Applied Computational Intelligence and Informatics*. IEEE, 2015, pp. 111—116.

58. **Li G., Xu H., Lin Y.** Application of bat algorithm based time optimal control in multi-robots formation reconfiguration, *Journal of Bionic Engineering*, 2018, vol. 15, no. 1, pp. 126—138.

59. **Furukawa T. et al.** Time-optimal coordinated control of the relative formation of multiple vehicles, *Proceedings 2003 IEEE International Symposium on Computational Intelligence in Robotics and Automation. Computational Intelligence in Robotics and Automation for the New Millennium (Cat. No. 03EX694*). IEEE, 2003, vol. 1, pp. 259—264.

60. **Borhaug E., Pavlov A., Pettersen K. Y.** Cross-track formation control of underactuated autonomous underwater vehicles, *Group Coordination and Cooperative Control,* Springer, Berlin, Heidelberg, 2006, pp. 35—54.

61. **Roy D., Maitra M., Bhattacharya S.** Study of formation control and obstacle avoidance of swarm robots using evolutionary algorithms, *2016 IEEE International Conference on Systems, Man, and Cybernetics (SMC)*. IEEE, 2016, pp. 3154—3159.

62. **Tan K. H., Lewis M. A.** Virtual structures for high-precision cooperative mobile robotic control, *Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems. IROS'96,* IEEE, 1996, vol. 1, pp. 132—139.

63. **Lau K. H.** Jet Propulsion Lab, *Personal Communication*, 2000.

64. **Qian X., De La Fortelle A., Moutarde F.** A hierarchical model predictive control framework for on-road formation control of autonomous vehicles, *2016 IEEE Intelligent Vehicles Symposium (IV),* IEEE, 2016, pp. 376—381.

65. **Low C. B.** Adaptable virtual structure formation tracking control design for nonholonomic tracked mobile robots, with experiments, *2015 IEEE 18th International Conference on Intelligent Transportation Systems,* IEEE, 2015, pp. 1868—1875.

66. **Essghaier A. et al.** Co-leaders and a flexible virtual structure based formation motion control, *International journal of vehicle autonomous systems*, 2011, vol. 9, no. 1—2, pp. 108—125.

67. **Chen L., Baoli M.** A nonlinear formation control of wheeled mobile robots with virtual structure approach, *2015 34th Chinese Control Conference (CCC),* IEEE, 2015, pp. 1080—1085.

68. **Benzerrouk A. et al.** Navigation of multi-robot formation in unstructured environment using dynamical virtual structures, *2010 IEEE/RSJ International Conference on Intelligent Robots and Systems*. IEEE, 2010, pp. 5589—5594.

69. **Vilca J., Adouane L., Mezouar Y.** Stable and Flexible Multi-Vehicle Navigation Based on Dynamic Inter-Target Distance Matrix, *IEEE Transactions on Intelligent Transportation Systems,* 2018, vol. 20, no. 4, pp. 1416—1431.

70. **Benzerrouk A., Adouane L., Martinet P.** Stable navigation in formation for a multi-robot system based on a constrained virtual structure, *Robotics and Autonomous Systems*, 2014, vol. 62, no. 12, pp. 1806—1815.