DOI: http://doi.org/10.25728/cs.2022.1.5

GROUP CONTROL OF UNMANNED AERIAL VEHICLES: A GENERALIZED PROBLEM STATEMENT OF APPLYING ARTIFICIAL INTELLIGENCE TECHNOLOGIES

V.P. Kutakhov[1] and R.V. Mescheryakov[2]

[1]National Research Center "Zhukovsky Institute," Moscow, Russia

[2]Trapeznikov Institute of Control Sciences, Russian Academy of Sciences, Moscow, Russia

✉ kutahovvp@nrczh.ru, ✉ mrv@ieee.org

Abstract. This paper considers elements of a group of unmanned aerial vehicles (UAVs) to form various tasks of the group and within a group of aerial systems. Different phases to execute control actions for a group of aerial systems of UAVs are proposed. These phases are shown by an example of selecting different targets for group elements (UAVs). The phases are elements of the large-scale behavior of the group and in the group of UAVs and can be included in the cycle when using artificial intelligence technologies. The approach is formalized for single-function UAVs (choosing a set of end actions) and multifunction UAVs (performing one or more impact functions within the group). A group control problem for applying artificial intelligence technologies is stated. The main elements of the system of relations and conditions for effectively performing tasks by a group of UAVs and executing actions within the group as a large-scale system are formulated. This system reflects the problem statement for applying artificial intelligence technologies. As noted, using homogeneous and heterogeneous groups of UAVs is a promising approach to interpret the formal behavior of robotic systems.

Keywords: UAV, robotics, unmanned aerial systems, artificial intelligence.

INTRODUCTION

Prospects for the development of unmanned technology, especially unmanned aerial systems, are associated with group application, the creation of large groups of heterogeneous unmanned aerial vehicles (UAVs), deeply informationally interconnected and acting together in the interests of a common task. When creating such unmanned systems (large-scale objects), a significant place should be assigned to the methods and technologies of artificial intelligence (AI) being intensively developed nowadays. This paper discusses approaches to UAV group control and directions for using AI technologies in the collective application of UAVs. In contrast to control of an individual UAV, group control of UAVs has a distinctive feature (see below): the latter is a sequence of decision-making subproblems and, to a lesser extent, dynamic subproblems for implementing these decisions.

Currently, the unmanned technology is dominated by remotely piloted means with the "natural intelligence" of the operator. The unreliability or overload of communication lines and the predicted mass application of UAVs, coming into conflict with the acceptable number of operators, lead to a transition to partially or fully autonomous control. Hence, there is the need to intensify research towards the autonomous actions of UAVs and their groups [1].

Artificial intelligence technologies are currently focused primarily on applications in UAV control systems and UAV payloads. Two single UAVs, one with artificial intelligence elements and the other without them, were compared in [2]. As demonstrated, perception, decision-making, behavior, and learning determine the efficiency of detection evaluated by errors of the first and second kind. Higher assessments were given to UAVs with artificial intelligence technology. Of course, there are wide-spread solutions of *simulta-*

neous localization and mapping (SLAM) problems for UAVs using AI technology [3]; breakthrough results would hardly appear soon.

Several publications considered particular problems of applying AI technologies in the operation of UAVs. For example, the paper [4] presented an onboard detection, tracking, and target evasion system for low-cost UAV flight controllers using artificial intelligence technologies. Data processing methods are commonly used to handle information from vision systems for navigation [5], reconnaissance (search and recognition of objects of interest [6, 7]), and control [8]. Frameworks for embedding AI technologies in UAVs are actively developing [9]. Any control system needs cybersecurity [10–14]. The original results in this area are methods of controlling control channels and counteracting attacks on them, particularly implementing *the smart city concept*.

As we believe, the most promising and effective application of AI should be considered in the field of unmanned systems for various purposes (even more promising, in the creation of large-scale multifunction unmanned systems [15]). Such systems can perform different tasks in agriculture [16, 17], forest protection and bioprotection [18], power line maintenance [19], motion control, natural and man-induced disasters [20, 21] (delivery, evacuation, transportation, and other tasks following current requests). Perhaps, such solutions will appear in the defense industry [22, 23]. Modern swarm control and MANET (*Mobile Ad hoc NETwork*) communication technologies are of interest to combine efficient organization in a group [13, 24]. However, they do not provide conditions for developing a full-fledged heterogeneous system.

In the near future, it is necessary to consider the use of large-scale information-executive aerial systems of UAVs [15]. They consist of informationally interconnected heterogeneous UAVs. It seems reasonable that these systems should consist of single-function UAVs for different information and executive purposes.

When organizing and controlling large groups of UAVs, much attention should be paid to the following aspects: a new set of problems associated with the deep group interaction of vehicles that form a diverse group when executing complex (often ill-defined) actions; new approaches and methods to solve the problems of group control.

In the concept of autonomous behavior of UAVs (particularly aerial systems of UAVs), the key role is assigned to control intellectualization for the behavior of individual vehicles in the group to coordinate their actions when performing a common task. Here, a separate place is occupied by decision-making (implementing methods and techniques of actions and distributing functions in the collective actions of UAVs within a complex target of the aerial system of UAVs. In the case of elementary targets, it is possible to use traditional methods of creating appropriate intelligent control algorithms [23]. However, with the complication of these targets and a significant increase in the group size, the reasonability and even need to apply artificial intelligence (AI) technologies become apparent.

Therefore, it is required to formalize intellectualization problems for aerial systems of UAVs: structure them, identify separate subproblems, and determine adequate methods to solve them using AI technologies.

1. PHASES TO SOLVE CONTROL PROBLEMS FOR AERIAL SYSTEMS OF UAVS

To concretize the AI problem statements, we deploy the actions of the aerial systems of UAVs into phases under a given target. Each phase can be assigned a scientific problem on control of group actions and decision-making (choosing an appropriate action method). Let us define separate control problems for aerial systems of UAVs necessary to implement in these phases.

Phase 1 is to determine the group's composition based on the target. The problem here is to form a rational composition of a group of heterogeneous, single-function UAVs based on the planned spatial range of actions (the area of operation) and a priori data about the objectives, conditions of actions, and available resources. This is a decision problem under constraints. The problem is complicated by uncertain a priori data and the blurred prediction of the a priori data for the period of the group's approach. Moreover, which is very important for the large-scale application of UAVs, the problem is complicated by the uncertain target formulation (e.g., carrying out a set of measures in the disaster zone with maximum efficiency).

Phase 2 is to manage group formation in the area of operation. This is building an appropriate spatial configuration of the group based on the functional capabilities of its elements. Nowadays, this problem is solved by an expert, even for small groups of executors. This problem should also be related to decision-making.

Phase 3 is to monitor the area of responsibility by various information means of different spatially distributed UAVs, detect target objects using combined information from heterogeneous information systems, and assess the situation in the area of operation. Let situation assessment be defined as a decision problem.

Phase 4 is to allocate the targets (i.e., distribute particular actions over particular objects among the UAVs of the group). This decision problem will be considered below.

Phase 5 is to designate the targets according to the allocation results considering the spatial location of UAVs and objects, the impact of the environment, and the differences and peculiarities of the information features of objects.

Phase 6 is to assess the effectiveness of actions and the technical state of the group elements.

Phase 7 is to reconfigure the aerial system of UAVs (perform Phase 3 again under new current conditions).

This phase deployment is conditional and illustrative. The phases may be combined in time. (In this case, the listed subproblems become significantly complicated.) For example, the reconfiguration process may occur in any phase depending on the variable conditions of the target.

In addition, this list of subproblems can be supplemented with those of managing information interaction in the group, selecting the hierarchical structure of group control in each stage, and some others. (Their analysis goes beyond the scope of this paper.) Moreover, it is often impossible to separate them into a phase.

Generally speaking, there are many subproblems and technologies to solve them within the scientific problems on UAV group control and their information interaction discussed above. Many of them partially overlap. We repeatedly emphasize that if the groups are small, these subproblems can be solved by traditional ways and methods; when the group scale increases, AI methods and technologies should be applied. And the most difficult problem (the megaproblem for AI) is to form control by solving all these subproblems.

2. CONTROL OF AERIAL SYSTEMS OF UAVS: PROBLEM STATEMENT

Let us return to the scientific problems on group control of UAVs (aerial systems of UAVs). As declared above, each phase can be assigned a scientific problem, and a rational solution should be obtained for it. We formalize the problem statement corresponding to Phase 4 (target allocation); see the figure below.

Consider a group of N UAVs formed in the previous phases. Each UAV i has a particular function. The set of UAVs is represented by the N-dimensional vectors of their coordinates r_i and properties q_i. The group includes UAVs equipped with information systems to detect and recognize objects (optoelectronic, radar, and electronic reconnaissance means). The group also includes UAVs with impact means, transport UAVs, etc. A special UAV (leader) may be assigned to control the group and organize interaction. The entire group is united in a single information space.

In addition, consider a group of objects detected and identified during the previous phases: M objects with the numbers $j=1, ..., M$, coordinates r_j, and properties q_j. The elements of groups N and M are distributed in space and are moving: their current coordinates depend on time t. All UAVs from group N have some relations with each object from group M; see the arrows in the figure. (Only some of them are shown in the figure for compact presentation.)

First, we present a system of relations: a matrix describing the geometric distances between elements i and j:

$$\rho(t)=\begin{pmatrix}\rho_{11}(t) & \cdots & \rho_{1M}(t)\\ \vdots & \rho_{ij}(t) & \vdots\\ \rho_{N1}(t) & \cdots & \rho_{NM}(t)\end{pmatrix}.$$

These distances, to some extent, determine the potential capabilities of elements i to search and detect elements j and impact the latter by appropriate means.

Group N contains information elements: single-function UAVs equipped with various information means (radar, optoelectronic, and electronic reconnaissance) described by the properties q_i.

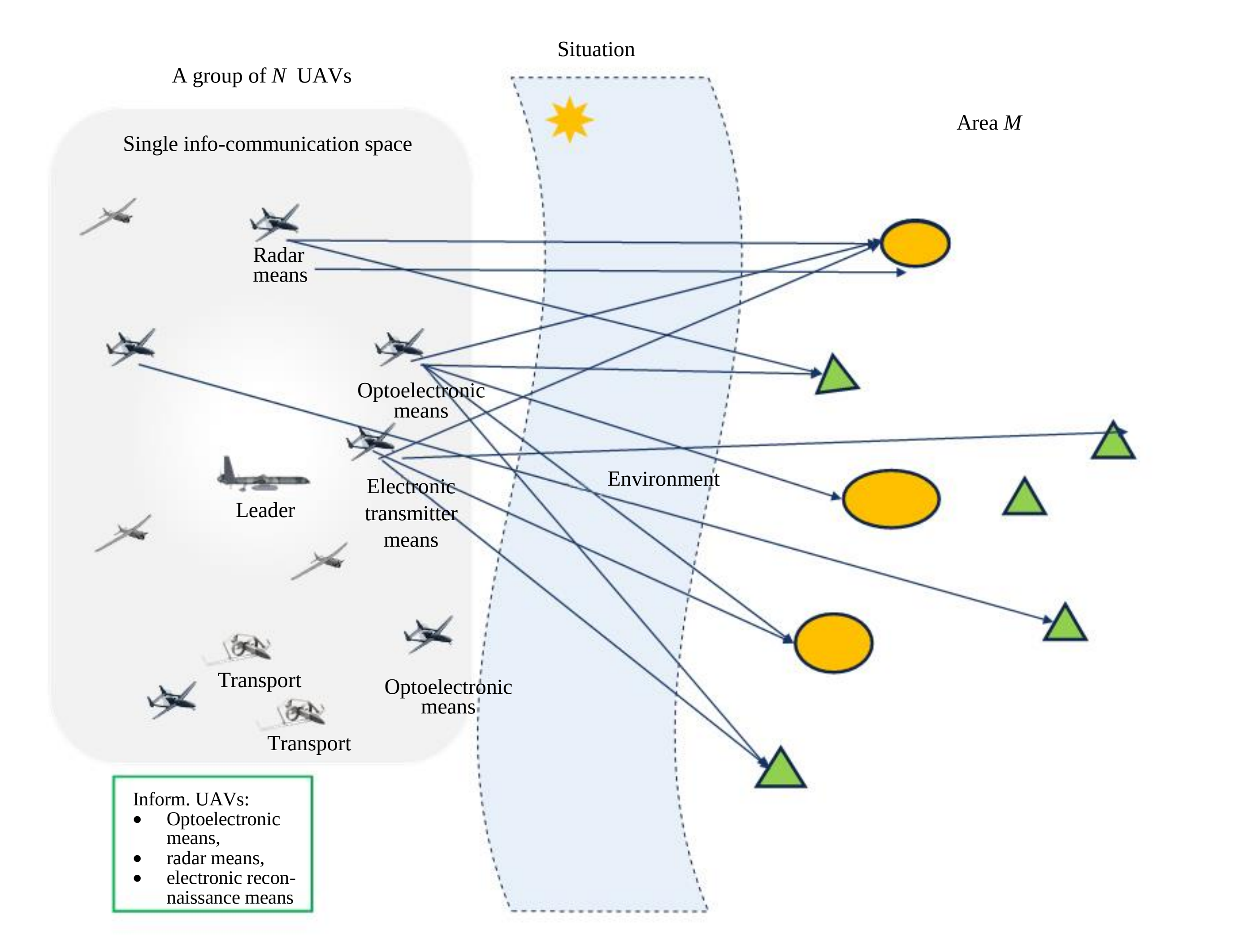
Group M includes objects with different information attributes and different reliability of detection and identification using information means with the properties q_i. Therefore, the information capabilities of each UAV with respect to objects can be represented by a system of information relations of the form

$$S(t)=\begin{pmatrix}S_{11}(t) & \cdots & S_{1M}(t)\\ \vdots & S_{ij}(t) & \vdots\\ S_{N1}(t) & \cdots & S_{NM}(t)\end{pmatrix}.$$

The elements S_{ij}, of course, depend on many factors (particularly the distances, the properties of objects and the environment, and others).

Elements from group M can be impacted by different means from group N to different degrees. The degrees depend on the impact means mounted on UAVs and the properties of the objects with respect to these means. The system of impact relations can be written as

$$B(t)=\begin{pmatrix}B_{11}(t) & \cdots & B_{1M}(t)\\ \vdots & B_{ij}(t) & \vdots\\ B_{N1}(t) & \cdots & B_{NM}(t)\end{pmatrix}.$$



The interaction scheme of a group of UAVs with objects in the target allocation phase: inform. UAVs—information UAVs; leader—the UAV deciding on the group application scenario.

Of course, these matrices contain zero elements for the impact UAVs (the system of information relations *S*) and the information support UAVs without impact means. (The expressions above are only matrix representations, and their elements are much more complex.)

An environment in the space between elements *i* and *j* affects the elements of the information and impact relation matrices:

$$E(t)=\begin{pmatrix} E_{11}(t) & \cdots & E_{1M}(t) \\ \vdots & E_{ij}(t) & \vdots \\ E_{N1}(t) & \cdots & E_{NM}(t) \end{pmatrix}.$$

Note that all elements of the matrices mentioned depend on time *t* in the operation process.

Next, the target allocation procedure needs an optimization criterion for the problem solution. As we believe, such a criterion can be the predicted efficiency of the impact of all elements *i* on all elements *j* considering the information support of their actions. Hence, the criterion can be written as

$$\mathrm{Eff}_{\max}=Y\big(B(\rho,\ S,\ E,\ t)\big),$$

where Eff is some function (functional) determining the generalized efficiency of the UAV group actions on the objects. It depends on *Q* (the distribution of tasks between the UAVs). The formation of this function is beyond the scope of this paper and will be considered separately. In the limit case, the optimization problem should be solved in real time using the onboard computers of UAVs.

The target allocation problem is to find a matrix *Q* consisting of values 0 or 1 (whether element *i* is assigned to interact with object *j* or not):

$$Q(t)^* = \begin{pmatrix} & \cdots & \\ \vdots & Q_{ij} & \vdots \\ & \cdots & \end{pmatrix}.$$

It seems that under sufficiently large dimensions of the matrices, these procedures can be obtained only using AI methods and technologies. Here, we do not analyze AI methods and technologies as applied to the listed subproblems. This paper considers a set of individual subproblems, mainly decision ones, constituting the general control problem for an intelligent autonomous group of objects.

The formal procedure for solving a particular target designation problem in the group control of UAVs has been described. It is suitable for organizing the actions of robotic groups, and the proposed approach to solve it is universal and has wide application [15].

Other components of the control problem for groups of UAVs (large-scale aerial systems of UAVs) can be described by analogy, including:

– organizing the structure of information interactions between group elements based on the current and predicted configuration and forming and reconfiguring the local information field;

– reconfiguring the group depending on changes in the targets' state, the detection of new objects, and the technical state dynamics of the group elements;

– combining information from spatially distributed sources via sensors with different signal structures and assessing the situation based on this information;

– forming a hierarchy for solving information-control subproblems in the group;

– forming a hierarchy for solving control subproblems in the group.

A significant part of these control subproblems is decision-making or discrete ones requiring specific solution principles. Of course, besides the listed subproblems, it is necessary to create specialized UAVs for group work and collective behavior to perform complex aerial tasks.

CONCLUSIONS

This paper has considered the range of subproblems and ways to solve them when creating control means and systems for heterogeneous multicomponent groups of UAVs. Such vehicles are designed to carry out complex activities for different, often ill-defined targets. Of course, each subproblem can be structured into several smaller-scale scientific problems. The subproblems discussed above would require using AI technologies along with traditional approaches. One of such subproblems—target allocation in a group—has been formalized in detail. The subproblems were previously considered in a superficial way without a generalized statement of applying artificial intelligence technologies in a group of UAVs; see [2, 8, 13, 14].

Despite the seeming long-term character of the general problem, research on the set of subproblems listed above should be deployed even now.

REFERENCES

1. URL: http://www.kremlin.ru/acts/bank/44731 (Accessed December 1, 2021.)
2. Li, C., Artificial Intelligence Technology in UAV Equipment, *Proceedings of 2021 IEEE/ACIS 20th International Fall Conference on Computer and Information Science* (*ICIS Fall*), Xi'an, China, 2021, pp. 299–302, DOI: 10.1109/ICISFall51598.2021.9627359.
3. Xia, C. and Yudi, A., Multi-UAV Path Planning Based on Improved Neural Network, *Proceedings of 2018 Chinese Control and Decision Conference* (*CCDC*), Shenyang, China, 2018, pp. 354–359, DOI: 10.1109/CCDC.2018.8407158.
4. Varatharasan, V., Rao, A.S.S., Toutounji, E., et al., Target Detection, Tracking and Avoidance System for Low-cost UAVs using AI-Based Approaches, *Proceedings of 2019 Workshop on Research, Education and Development of Unmanned Aerial Systems* (*RED UAS*), Cranfield, UK, 2019, pp. 142–147, DOI: 10.1109/REDUAS47371.2019.8999683.
5. Hu, A.-P., Camera Calibration for UAV Ground Feature Localization, *Proceedings of 2011 IEEE/ASME International Conference on Advanced Intelligent Mechatronics* (*AIM*), Budapest, Hungary, 2011, pp. 176–179, DOI: 10.1109/AIM.2011.6027132.
6. Zheng, L., Ai, P., and Wu, Y., Building Recognition of UAV Remote Sensing Images by Deep Learning, *Proceedings of 2020 IEEE International Geoscience and Remote Sensing Symposium* (*IGARSS 2020*), Waikoloa, HI, USA, pp. 1185–1188, DOI: 10.1109/IGARSS39084.2020.9323322.
7. Zhang, Y., McCalmon, J., Peake, A., et al., A Symbolic-AI Approach for UAV Exploration Tasks, *Proceedings of 2021 7th International Conference on Automation, Robotics and Applications* (*ICARA*), Prague, Czech Republic, 2021, pp. 101–105, DOI: 10.1109/ICARA51699.2021.9376403.
8. Chen, B., Research on AI Application in the Field of Quadcopter UAVs, *Proceedings of 2020 IEEE 2nd International Conference on Civil Aviation Safety and Information Technology* (*ICCASIT*), Weihai, China, 2020, pp. 569–571, DOI: 10.1109/ICCASIT50869.2020.9368551.
9. Tootogogtokh, E., Huang, S., Leong, W.L., et al., An Efficient Artificial Intelligence Framework for UAV Systems, *Proceedings of 2019 Twelfth International Conference on Ubi-Media Computing* (*Ubi-Media*), Bali, Indonesia, 2019, pp. 47–53, DOI: 10.1109/Ubi-Media.2019.00018.
10. Kim, H., Ben-Othman, J., Mokdad, L., et al., Research Challenges and Security Threats to AI-Driven 5G Virtual Emotion Applications Using Autonomous Vehicles, Drones, and Smart Devices, *IEEE Network*, 2020, vol. 34, no. 6, pp. 288–294, DOI: 10.1109/MNET.011.2000245.
11. Jharko, E.F., Promyslov, V.G., Iskhakova, A.Yu., et al., *Kiberbezopasnost' bespilotnykh transportnykh sredstv. Arkhitektura. Metody proektirovaniya* (Cybersecurity of Unmanned Vehicles. Architecture. Design Methods), Moscow: Radiotekhnika, 2021. (In Russian.)

12. Wang, Y., Su, Z., Zhang, N., and Benslimane, A., Learning in the Air: Secure Federated Learning for UAV-Assisted Crowdsensing, *IEEE Transactions on Network Science and Engineering*, 2021, vol. 8, no. 2, pp. 1055–1069, DOI: 10.1109/TNSE.2020.3014385.
13. Kusyk, J., Uyar, M.U., Ma, K., et al., AI and Game Theory Based Autonomous UAV Swarm for Cybersecurity, *Proceedings of 2019 IEEE Military Communications Conference* (*MILCOM*), Norfolk, VA, USA, 2019, pp. 1–6, DOI: 10.1109/MILCOM47813.2019.9020811.
14. Molina-Padrón, N., Cabrera-Almeida, F., Araña, V., et al., Monitoring in Near-Real Time for Amateur UAVs Using the AIS, *IEEE Access*, 2020, vol. 8, pp. 33380–33390, DOI: 10.1109/ACCESS.2020.2973503.
15. Kutakhov, V.P. and Plyaskota, S.I., Information Interaction in Large-Scale Robotic Aviation Systems, *Trudy 10-oi mezhdunarodnoi konferentsii "Upravlenie razvitiem krupnomasshtabnykh sistem"* (Proceedings of the 10th International Conference "Management of Large-scale Systems Development" (MLSD'2017)), Vassilyev, S.N. and Tsvirkun, A.D., Eds., Moscow: Trapeznikov Institute of Control Sciences RAS, 2017, pp. 93–96. (In Russian.)
16. Shevchenko, A.V., Meshcheryakov, R.V., and Migachev, A.N., Review of the World Market of Agriculture Robotics. Part 1. Unmanned Vehicles for Agriculture, *Control Sciences*, 2019, no. 5, pp. 3–18. (In Russian.)
17. Shevchenko, A.V., Meshcheryakov, R.V., and Migachev, A.N., Review of the World Market of Agriculture Robotics. Part 2. Unmanned Aerial Vehicles and Robotic Farms, *Control Sciences*, 2019, no. 6, pp. 3–10. (In Russian.)
18. Wang, X., Wang, X., Zhao, J., et al., Monitoring the Thermal Discharge of Hongyanhe Nuclear Power Plant with Aerial Remote Sensing Technology Using a UAV Platform, *Proceedings of 2017 IEEE International Geoscience and Remote Sensing Symposium* (*IGARSS*), Fort Worth, TX, USA, 2017, pp. 2958–2961. DOI: 10.1109/IGARSS.2017.8127619.
19. Zhang, S., Wu, X., Zhang, G., et al., Analysis of Intelligent Inspection Program for UAV Grid Based on AI, *Proceedings of 2020 IEEE International Conference on High Voltage Engineering and Application* (*ICHVE*), Xi'an, China, 2020, pp. 1–4, DOI: 10.1109/ICHVE49031.2020.9279634.
20. Moranduzzo, T. and Melgani, F., Monitoring Structural Damages in Large Industrial Plants with UAV Images, *Proceedings of 2014 IEEE Geoscience and Remote Sensing Symposium*, Quebec City, QC, Canada, 2014, DOI: 10.1109/IGARSS.2014.6947606.
21. Kim, M.L. Kosterenko, V.N., Pevzner, L.D., et al. Automatic Trajectory Motion Control System for Mine Unmanned Aircrafts, *Russian Mining Industry Journal*, 2019, vol. 3 (145), pp. 60–64. (In Russian.)
22. Yevtodyeva, M. and Tselitsky, S.V., Military Unmanned Aerial Vehicles: Trends in Development and Production, *Pathways to Peace and Security*, 2019, no. 2 (57), pp. 104–111. (In Russian.)
23. Kutakhov, V.P. and Meshcheryakov, R.V., Principles to Form an Optimization Model of a Robotic Aerial System, *Trudy 13-go Vserossiiskogo soveshchaniya po problemam upravleniya* (*VSPU-2019*) (Proceedings of the 13th All-Russian Meeting on Control Problems (AMCP-2019)), Moscow: Trapeznikov Institute of Control Sciences RAS, 2019, pp. 1211–1214. (In Russian.)
24. Kusyk, J., Uyar, M.U., Ma, K., et al., AI Based Flight Control for Autonomous UAV Swarms, *Proceedings of 2018 International Conference on Computational Science and Computational Intelligence* (*CSCI*), Las Vegas, NV, USA, 2018, pp. 1155–1160, DOI: 10.1109/CSCI46756.2018.00223.

This paper was recommended for publication by P.Yu. Chebotarev, a member of the Editorial Board.

Received January 20, 2021, and revised January 7, 2022.
Accepted January 17, 2022.

Author information

Kutakhov, Vladimir Pavlovich. Dr. Sci. (Eng.), National Research Center "Zhukovsky Institute," Moscow, Russia
✉ kutahovvp@nrczh.ru

Meshcheryakov, Roman Valer'evich. Dr. Sci. (Eng.), Trapeznikov Institute of Control Sciences, Russian Academy of Sciences, Moscow, Russia
✉ mrv@ieee.org

Cite this paper

Kutakhov, V.P., Meshcheryakov, R.V., Group Control of Unmanned Aerial Vehicles: A Generalized Problem Statement of Applying Artificial Intelligence Technologies. *Control Sciences* **1,** 55–60 (2022). http://doi.org/10.25728/cs.2022.1.5

Translated into English by *Alexander Yu. Mazurov*,
Cand. Sci. (Phys.–Math.),
Trapeznikov Institute of Control Sciences,
Russian Academy of Sciences, Moscow, Russia
✉ alexander.mazurov08@gmail.com