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ON THE FRACTAL THEORY APPLICATION IN ADAPTIVE POPULATION METHODS OF FORMATION OF DYNAMICAL GROUPS OF UNMANNED AERIAL VEHICLES AND IN PROCESSING OF INCOMING INFORMATION IN RESPECT TO ITS EFFECTIVE APPLICATION THEORY

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Solution of complicated complex problems is possible only as a result of group application of unmanned aerial vehicles (UAV). Approaches to studying game-theoretical problems of the information confrontation have been given in the framework of stochastic control models. This is about organization of "distributed intelligence" and collective interactions of UAVs in group, designing assets of informational exchange and forming distributed data bases and knowledge bases, designing methods and algorithms of group decision-making and adaptive control in conditions of dynamically changing natural environment. Distributed control systems with minimization of information exchange between group UAVs have been considered as well. An important role is allocated to modern methods of images processing and patterns recognition. A task of detecting objects including stealthy ones at fuzzy images which are obtained from UAV has been considered. As before the investigation is conducted within the framework of fractal-scaling thresholding including an adaptive threshold. Fractal approaches to solution of such problems at every stage of processing and realization of incoming information have been proposed in the work.

Keywords: Unmanned aerial vehicle, population algorithms, swarmalgorithms, radiolocation, game theory, fractal, image processing

Introduction

Unmanned aerial vehicles (UAVs) are currently used to solve a wide range of scientific and practical problems and they can become the main element of the formation of a global information field [1-9]. It can be said that now there is a rapid development of pilotless aircraft. Using located at the aircraft optical, radar and infrared sensors, it is possible to obtain digital high-resolution images and a high degree of operational efficiency at any time of the day. The following modes are possible: sweeping of a preselected terrain sector; target search along a linear route; route mapping; obtaining detailed images of small areas of interest as well as objects located there. A wide field of view of sensors makes it possible to sweep the terrain regardless of UAV maneuvers. According to [3, 7], the "Aviation Week and Space Technology" journal predicts the share of the world market of UAVs in 2014-2023 to be about 67 billion US dollars. Then the estimated costs will be distributed as follows: R & D work will cost $ 28.7 billion; UAVs production will cost 35.6 billion dollars; and service will cost 2-3 billion dollars.

The current stage of development of the world aircraft industry is characterized by the rapid development of drone aircraft. According to "Rosoboronexport" experts, at present more than 50 companies in 40 countries of the world develop and produce more than 600 types of UAVs [3, 7]. The leading position in terms of their variety and production volume is taken by the United States (32.5%) followed by countries such as Israel (6.4%), France (5.7%), England (5.6%), Russia (5.5%), Germany (4.0%), Italy (3.4%), Spain (3.0%), Iran (2.9%) and China (2.4%). The share of the rest of the world is 28.5%.

1. Group interaction of UAV

The solution of complex tasks is only possible as a result of use of a UAV group. A group is a set of a number of similar or different types of UAVs, united by a common target. According to [1, p. 652-653], the number of UAVs in typical formations can range from a few units to several tens.

A "heavy" brigade is a complex of battlefield reconnaissance drone "Shadow" that consists of 4 RQ-7 "Shadow" battlefield reconnaissance UAVs; a complex of "Raven"-10 battlefield reconnaissance mini-drones (by 3 RQ-11 "Raven" battlefield reconnaissance drones). A "light" brigade is a complex of battlefield reconnaissance drones "Shadow"-1 (4 RQ-7 "Shadow" battlefield reconnaissance drones); a complex of "Raven"-3 battlefield reconnaissance mini-drones (by 3 RQ-11 "Raven" battlefield reconnaissance drones). A "Stryker" brigade is a complex of "Shadow"-1 battlefield reconnaissance drones (four RQ-7 "Shadow" battlefield reconnaissance drones).

The use of UAV groups becomes a promising trend of aviation science and technology. The successful solution to this problem requires an integrated or system approach, which is not practically present in existing works on the use of unmanned aircraft. The first attempt to implement such an approach was made in monographs [7, 9]. In practice, it is possible to implement a significant number of types of UAV group flights. In the monograph [9], there is a classification of group flights of drones in the process of operational commitment of the group, such as planar trajectory flying of a UAV group, three-dimensional flight path of a drone group, UAV “swarm” flying, drone stream flying, UAV formation flying, flying of drones without crossing their trajectories, flying of UAVs crossing their trajectories, close formation flying of drones, break up flying of UAVs.

It should be noted that it is very important to develop theoretical foundations and practical procedures of organizing basic and auxiliary (service) processes of effective use of UAVs of various application [1-18]. Mass use of UAV groups in various military and civil areas implies a transition from piece-work to mass production of drones.

The problem of UAV group control (normally by robots) and its solution is a subject of increased interest of scientists and it is carried out using various iterative methods. Let us briefly consider some of them.

2. "Distributed intelligence" in UAV group interaction

In real conditions, UAVs operate in a nondeterministic, unpredictable environment and in conditions of counteraction. Each of drones performs a number of operations aimed at solving a common problem. In this case, it becomes necessary to distribute control on the field of solving problems. It is possible with minimal central control to ensure that the network would operate without congestion of traffic. It is necessary to draw a parallel with biological investigations, which attempt to answer the question of the emergence of cooperative behavior in the process of evolution or the so-called evolutionary strategy [10-14].

To effectively solve the problems of global optimization, in the 80-s of the last century, scientists began to intensively develop stochastic search algorithms for optimization. Intellectual or population algorithms (methods) refer to the class of stochastic search optimization algorithms. Population algorithms are included in the class of heuristic algorithms for which convergence to a global solution is not proved, but it has been experimentally established that they give a fairly good solution. According to [10], the scheme of population algorithms contains the following stages: 1 – initialization of the population; 2 – migration of agents of the population; 3 – end of the search. From the content of these stages follows the multiplicity of such algorithms due to the variation of the rules of initialization of the population, migration operators and the conditions for completing the search.

Properties of members or agents of the population (in our case, UAVs) are autonomy, stochasticity, limited representation, decentralization, communication skills. These properties of agents, even with their simplest behavioral strategies, contribute to the formation of swarm intelligence of the population, i.e., the "synergetic paradigm" with the laws of complex systems is in effect here. The ideological basis is the emergence effect of behavior in the theory system. That means that any system exhibits special properties which its elements do not possess. It is believed that relatively simple rules of individual behavior can create a complex organized behavior of the whole swarm. The key moment is the interaction between the members of the group that creates a system of constant feedback, and the objective function is the reasonableness of the behavior of the whole group of robots, not of an individual.

What do we have to gain by search optimization population algorithms? For poorly formalized problems with their frequent multimodality and high dimensionality, such algorithms provide a high probability of localization of the global extremum under a suboptimal solution. Adaptation and self-adaptation mechanisms provide a transition from diversification (an extensive overview of a search space) to intensification (the rate of convergence of the algorithm) of the search.

3. The classification of population algorithms

Several classifications of population optimization algorithms can be offered. In [10] the following classes of such algorithms are distinguished:

- evolutionary algorithms, including genetic algorithms;
- population algorithms inspired by wildlife (algorithms of a swarm of particles, colony of ants, a bee swarm, an artificial immune system, bacterial optimization, etc.);
- algorithms inspired by inanimate nature (harmonic, gravitational and electromagnetic search algorithms (or those of potential fields), etc.);
- algorithms, inspired by human society (algorithms for the evolution of reason, stochastic diffusion search, "cultural" algorithms, memetic algorithms, etc.);
- other algorithms (self-organizing migration algorithm, scattered search algorithms, navigation algorithms, etc.).

The application of the method of potential fields makes for creating different types of group control [11]: 1 – "a stayer race", the master robot is attracted to the target, and the other robots of the group are attracted to the leader; 2 – "a chain", the master-robot is attracted to the target, and each subsequent robot is attracted to the previous one; 3 – " divergence", the repulsive force from the leader acts on all other robots of the group that leads to the group dispersion; 4 – "convergence", an attractive force to the master robot acts on all other robots of the group; 5 – "free search", only repulse force from obstacles and other robots of the group act on the robots when they come too close to each other. In the method of potential fields, the simplicity of calculating the total forces is achieved, which are also easily implemented for low-power on-board computers installed in small-sized robots. This method only makes it possible to fall in formations of equidistant robots. Effective shaping of trajectories is possible only with a convex set of contours of environmental elements, otherwise it is necessary to use additional heuristic algorithms to eliminate local minima.

In the operation of UAVs in non-stationary environments with obstacles or conflict environments, the method of non-potential fields is widely used [11]. The main feature of this method is that a drone travels in the field of non-potential forces, that is, repellers (a repulsive set) and attractors (an attracting set) form repulsive or attracting forces that depend not only on the relative location of the UAVs and an obstacle, but also on speeds and additional free variables. Here the idea of forming unstable states in the phase space of control systems is used. The idea is taken from the theory of nonlinear dynamics and synergetics.

4. Swarm algorithms

The effectiveness of a ("swarm") UAV group is significantly increased when there is informational interaction between its members. Intellectual control methods rely on mathematical and logical operations. To process them, they require powerful computing resources and establishing adaptive communication networks (high survivability and flexibility of network topology) for information exchange. Thus, this means the organization of "distributed intelligence" and collective interaction of drones in a group, making information exchange tools and creation of distributed data and knowledge bases, development of methods and algorithms for making group decisions and adaptive control in a dynamically changing natural environment. A swarm can be controlled by only one operator, that is, it is necessary to include a person in the "swarm" control loop and ensure that the operator transmits control commands to partially meet the conditions for resistance to external influences.

The formation of a swarm is subject to a set of rules [13]: 1 – the rule of connection that ensures the connectivity of UAVs, focusing on their acceleration vectors in the direction of the local center of the swarm, provided that the distance between them is greater than some specified value; 2 – alignment rule that allows drones to travel at speeds with which its neighbours move; 3 – the rule of separation that allows each UAV to keep a distance between itself and its neighbours more than minimally necessary in order to prevent the overlapping of sensors; 4 – the rule of avoiding targets that provides an approach to the target at a distance no closer than a specified one (for example, until certain commands are received).

It is currently important to teach drones to fly like a flock of birds or a swarm of bees. As specially noted in [15], "... Then we will be able to control one device, and the rest will be controlled by this technology. And if the leader for some reason dies, the function of the leader of the pack ipso facto goes to the next. And so it will be until the last device is alive. And, for example, in combat operations this is a very important quality that no one has today. It is practically ineradicable, indestructible thing. This is what we are going to, doing things that are primitive from the point of view of the future. But when you start moving, it's important to see the ultimate goal."

5. On fractal approaches to the formation of dynamic UAV groups

The author's fractal-scaling method, long and widely known in the scientific world [14, 16-41], is also applicable to the solution of these problems. Suppose a complex network of a set of micro- (nano-) UAVs (>10^2...10^3) carries out a global monitoring of the territory and objects located there. The problem can be considered within the framework of the concept of a distributed measuring environment, where each point of a certain dynamic medium is capable of performing sensory, measuring and information functions [21, 24]. A fractal-graph approach makes it possible to study the growth of complex networks and gives a method of manipulating such networks at a global scale, without applying for a detailed description. In such a case, it turns out that an excessive number of sensors (drones) does not guarantee their optimal distribution in/over the nondeterministic medium under study. The introduction of a fractal topology of such networks, taking into account the configuration of the investigated territory, will make for more accurately and using fewer means (the number of UAVs) to monitor it detecting objects. It is not a question of few pro cents, but of a more substantial gain in necessary and sufficient number of drones.

In [16-19, 36-39], the problem of detecting objects, including subtle ones, in blurred pictures obtained by UAVs is considered. As before, the research is conducted within the framework of fractal-scaling threshold processing, including an adaptive threshold. At the same time, problems of processing images from drones based on the integer Lebesgue measure are also considered.

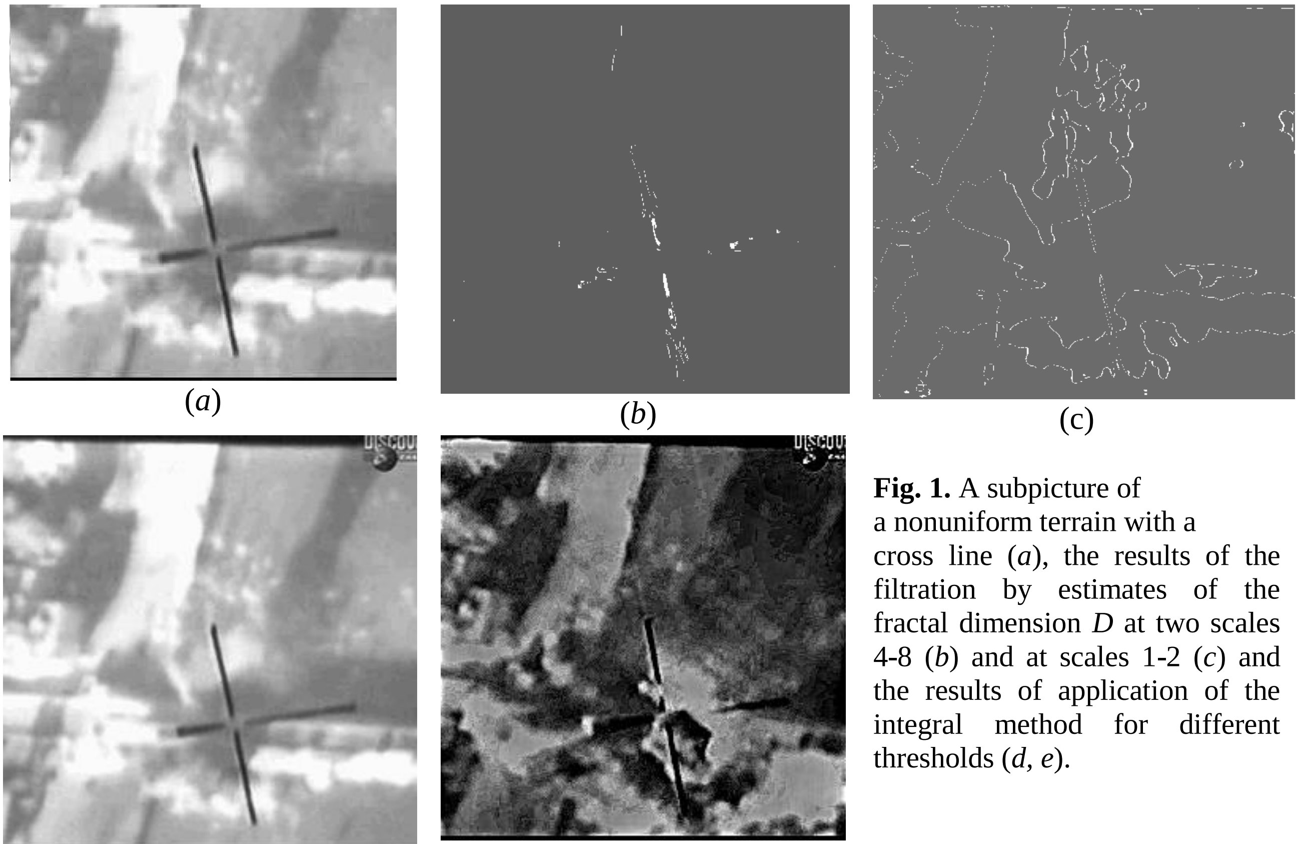
In the light of the formulation and improvement of solutions to the problems of collective interaction of UAVs, it is possible to apply the new concepts presented in our papers [34, 35] on guidance techniques and game theory with incomplete information.

The main means of new population algorithms development is to hybridize a known population algorithm with other population or non-population ones. When solving real-world problems, the problem of multicriteria optimization often arises. Most of the problems considered are based on an approach that takes into account their multicriteria and obtaining of a set of Pareto optimal variations of (unimprovable, effective) solutions. The most well-known Pareto-approximation algorithms are developed on the basis of evolutionary genetic algorithms.

6. Processing of fuzzy images obtained from UAVs by fractal scaling and integral methods

The following are the specific results of processing real images obtained from UAVs under conditions of flight over a nonuniform terrain with various objects. The processing was carried out by our own long-established fractal-scaling and integral methods. The authors also developed some methods of continual improvement of image quality in case of background distortions, brightness attenuation and distortion of the image form. These methods are based on the consistent application of iterative Fourier procedures with phase and amplitude correction by fractional power filters [21-23].

The results of the processing are shown in Fig. 1-3. The images were processed by local estimates of fractal dimension *D* and using the method of fractal signatures at two scales of observation. In processing, a wide range of scales was used. That made it possible to solve the problem of selecting areas and objects with characteristic relative sizes from 2 to 15.

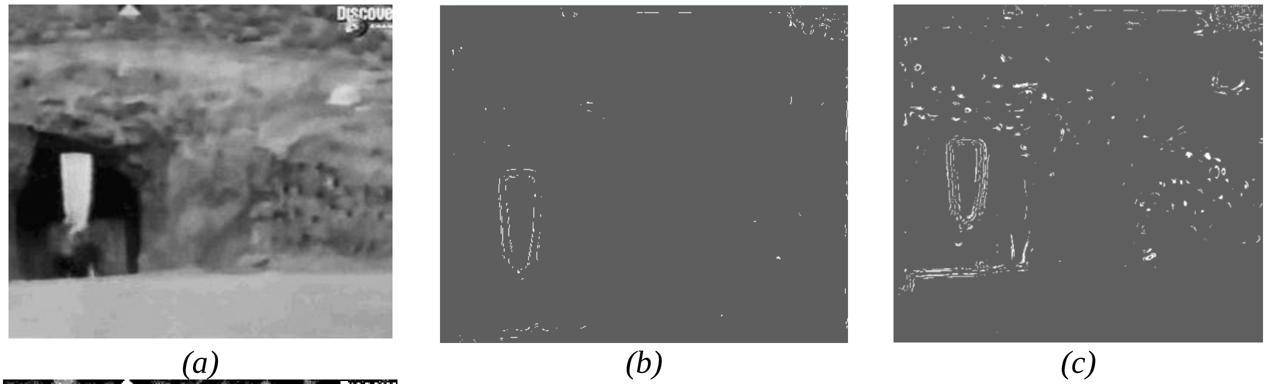

(*a*) (*b*) (c)

(d) (*e*)

Fig. 1. A subpicture of a nonuniform terrain with a cross line (*a*), the results of the filtration by estimates of the fractal dimension *D* at two scales 4-8 (*b*) and at scales 1-2 (*c*) and the results of application of the integral method for different thresholds (*d*, *e*).

When processing the image in Fig. 1, the problem of selecting a characteristic object – a "cross line", was solved. Using two scales of 4 and 8 points made it possible to solve that problem. Fig. 2 *a* shows the picture of a tunnel in the mountainous area obtained from a UAV. The results of the filtration by estimates of the fractal dimension *D* in two scales 3-5 (7 *b*) and 8-11 (2 *c*) are presented in the first line. Fig. 3 *a* shows the picture of an urban area with cars driving along a highway.

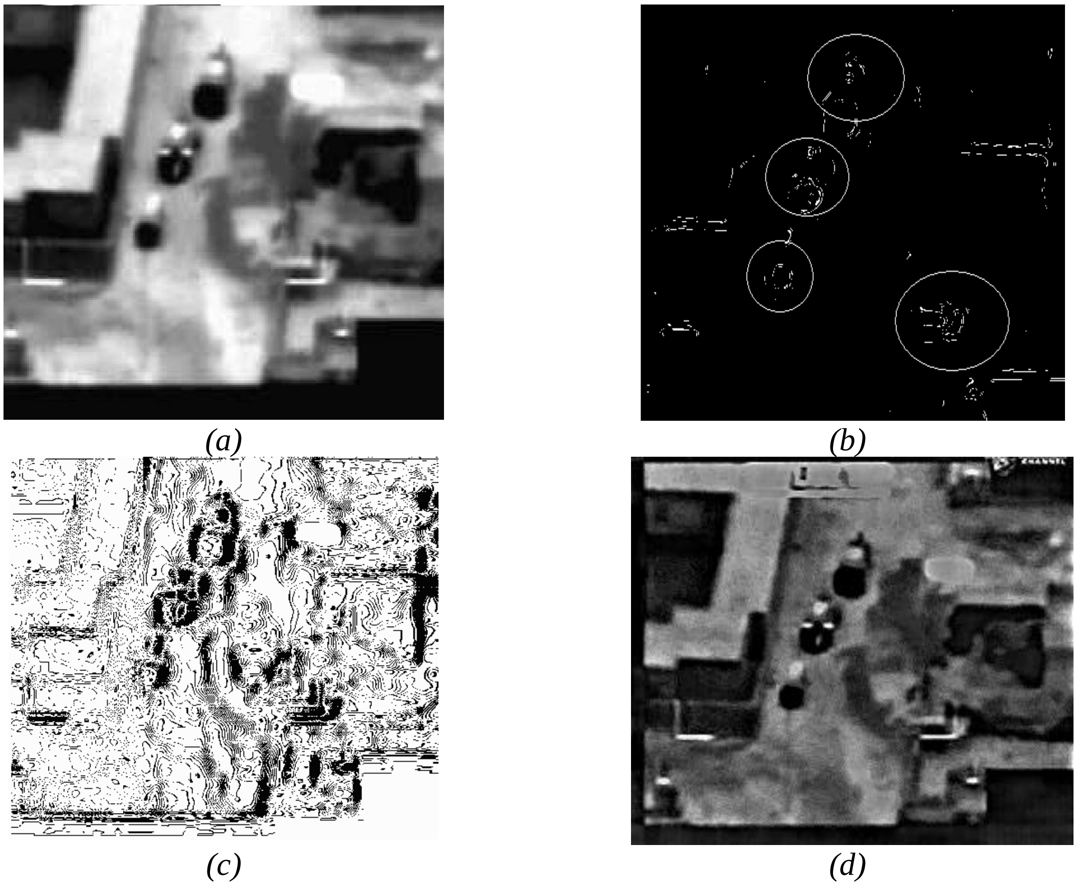
The results of the filtration by estimates of the fractal dimension *D* at a scale of 4-6 (3 *b*) are presented in the first line. The windows are selected to obtain the best results of car selection. Fig. 3*c* shows a chart of estimates of the fractal dimension *D* without filtration. The data of the integral method are presented in Fig. 3*d*. Some selected results of processing images from UAVs using the integer Lebesgue measure [18, 19, 23] are shown further in Fig. 4 -7.



(a) *(b)* *(c)*

(d)

Fig. 2. A subpicture of a mountainous area with a tunnel (*a*), the results of filtration by estimates of the fractal dimensionality *D* at two scales 3-5 (*b*) and at scales 8-11 (*c*), the result of application of the integral method (*d*).

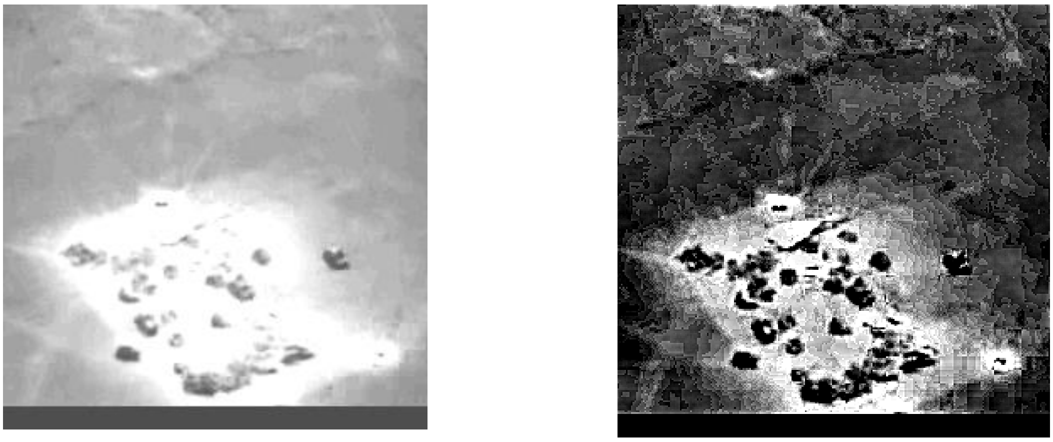


(a) *(b)*

(c) *(d)*

Fig. 3. A picture of an urban area with cars driving along a highway (*a*), the results of fractal filtration by estimates of the fractal dimension *D* at a scale of 4-6 (*b*), a full fractal chart of estimates of *D* over the field without filtration (*c*), and the results of application of the integral method (*d*).

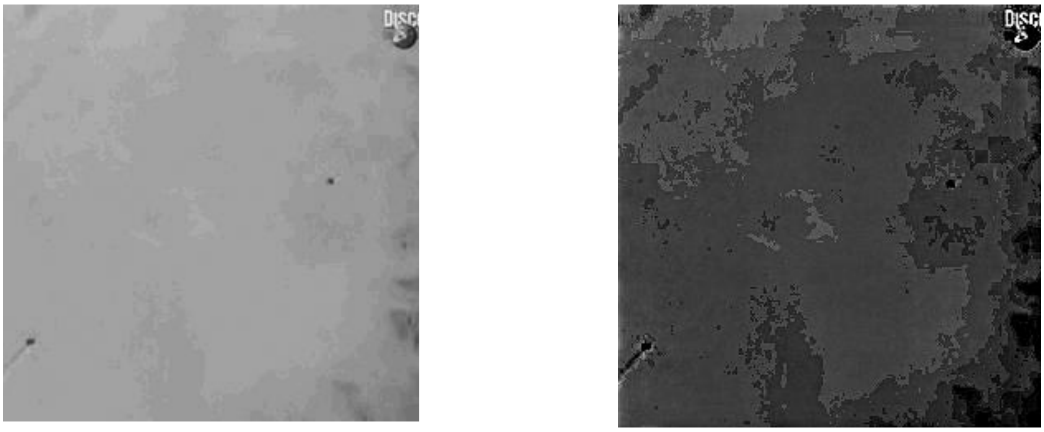
The selection of moving and stationary vehicles is shown in Fig. 4 and Fig. 6



(*a*) (*b*)

Fig. 4. The picture of a mass of traffic (*a*) and the results of processing based on our integral method (*b*).

The results of selection of images of natural extended objects in the conditions of fog and drizzling rain are shown in Fig. 5.



(*a*) (*b*)

Fig. 5. The picture of a water basin and saturated terrain in foggy rainy weather (*a*), the results of processing based on our integral method (*b*)

(*a*) (*b*)

Fig. 6. The picture of a caravan of cars *(a*) and the results of the processing on the basis of the integral method (*b*).

Fig. 7 shows the results processing of a picture with elements of an urban area, vehicles, vegetation, and the like taken from a UAV

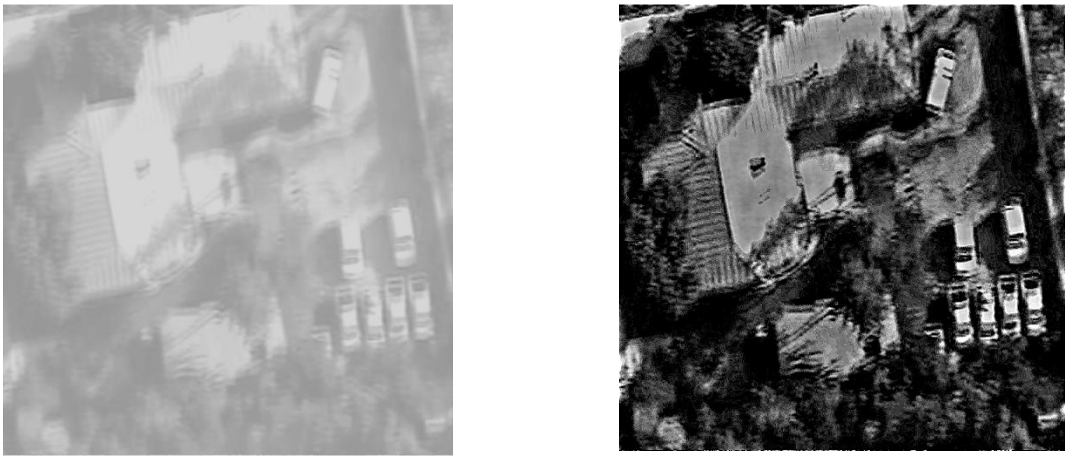

(*a*) (*b*)

Fig. 7. The picture with elements of an urban area, transport facilities, vegetation and the like (*a*); the results of processing based on the integral method (*b*).

The data presented demonstrate good performability of the proposed methods for processing images obtained during a passive mode of observation.

If practical applications require very fast processing – as soon as frames arrive, then it is possible to limit only to a modified method of brightness intensification and contrast enhancing of an image, as well as its fractal contouring.

7. On the development of the theory of effective use of UAVs

Let's briefly review the fundamentals of the theory of effective use of UAVs in monographs [4-9] [1]. Significant expenditures for the production of various types of drones make actual the problem of their effective operation in solving various military and civil tasks. As a retrospective analysis of the development of unmanned aircraft has shown [1, 3, 4-9, 15], the development, production and use of UAVs of various applications in our country and abroad is carried without a serious theoretical basis that takes into account all the characteristics of this type of aircraft .

In the opinion of Prof. V.S. Moiseyev [4-9], Russia's coming to the forefront in the design and production of a variety of unmanned equipment is impossible without the development and active application in practice of the general theory of automated design and production of UAVs. Equally important is the development of theoretical foundations and practical methods of organizing basic and auxiliary (service) processes for the effective use of UAVs for various applications. It should be noted that there is no sufficiently detailed consideration of such problems in the existing scientific and technical literature and periodicals.

Considered in monographs [4-9], most problems on the effective use of UAVs and remotely piloted aircraft systems (RPAS) are based on an approach that takes into account their multi-criteriality and obtaining of a set of Pareto optimal variations,

(unimprovable, effective) solutions. These variations should be given to the respective decision-maker to choose the solution to be used based on his experience, intuition and the current practical situation. If it is difficult to choose a particular solution, it is suggested to use the "ideal point" method, which makes it possible to point to the solution closest to the "ideal" solution of the multicriteria optimization problem under consideration in the Pareto optimal set.

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[1] All these inaccessible books were sent to the author by Professor V.S. Moiseev in the process of their correspondence and mutual exchange of the monographs written by them.

In monographs [4-9] the experience of applying a system approach to the effective organization of basic and auxiliary processes of using UAVs for various applications is presented. Further development of the proposed theory should be focused at intensification and expansion of the set of its tasks in terms of maximum approximation to the practice of operation of various, including promising, types of drones. At the present time, the theory of the effective use of UAVs and RPASs is urgently needed to be complemented by elements of the mathematical theory of fractals in combination with scaling effects, that is, those topical fields that we call fractal scaling or scale-invariant radiolocation [21, 22, 25 33, 39-41].

The most important aspect of the practical application of the results of the theory of effective use of UAV is the development and implementation of secure information and communication technologies to solve its problems. Users of such technologies, which should be implemented in a network-centric mobile UAV group distributed by an automated control system, are the personnel and the managerial (command) personnel of RPAS and corresponding unmanned units. A promising direction of development of the proposed theory is integration of pilotless units into tasks, methods and algorithms for the formation of UAV optimal control software that are directly related to the purposes of their application. As a result, a general theory of the effective use of UAVs should be developed, in which the theory of optimal control of drones for various applications will be an integral part.

By profound conviction of the authors [3, 4-9], it is possible achieve the world's leading positions in unmanned aircraft technology only with the active use of a serious theoretical basis for the development, production and use of UAVs and RPASs in practice.

Conclusion

The considered basic tendencies in the development of methods of group control inevitably require their intensification and expansion from the standpoint of the theory of the effective use of UAVs [4-9]. For the first time, it is proposed to introduce elements of fractal theory in combination with scaling effects into search algorithms and in the process of formation of dynamic UAV groups. The algorithms developed under such rules will make for successful control of a UAV group in the process of motion, search for targets, and deployment to a certain order and execution of target tasks.

Fractal-scaling methods, first proposed and developed by the author, are based on a constructive theory of fractional measure and can be considerably superior to classical methods of radio engineering and radiolocation in their capabilities. This proves and confirms the practical relevance of the fundamental theory of fractional measure.

As a result, in the scientific world a new semantic space has been formed, which possess properties and tasks that are unusual for classical physics. In this context, the central connecting concepts are "fractal, fractional operators, scaling, non-Gaussian statistics, fractional dimensional, sampling topology".

The idea of the advantages of fractal processing in radiolocation is the first to acquire the role of a guiding idea not only for explaining the principles and methods of signal processing but also for development of new fractal-scaling methods that were not considered before and for designing a fractal radar locator based on the concept of fractal radio systems proposed by the author [21, 22, 25-33, 36-41].

The presented results of processing of images of various types from UAVs show that developed by the author modern methods for information processing have high productivity, and they also improve in the quality and detailing of the processed images in the passive and active illumination mode by several times. These methods can be successfully applied to the processing of incoming information from space and other aircraft systems as well.

The obtained scientific results are the starting material for the further development and practical application of fractal methods in modern fields of radiophysics, radio engineering, radiolocation, electronics and information-control systems.

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