Reliability assessment of UAV fleets

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Abstract. UAVs have a great potential of application for monitoring, search, detection, communication, delivery and transportation of cargo in various sectors of economy. In spite of this, the existing software and hardware, as well as legal limitations, prevent the wide application of UAVs. There is intensive research related to automation and optimization of missions of one or more UAVs in various application areas. However, the execution of missions of both individual vehicles and their homogeneous or heterogeneous groups depends on the reliability issues of these technical devices, UAVs fleets, and control systems. In this paper, we present models for assessing fleet reliability of UAVs that are managed centralized or decentralized. The method is based on the representation of the fleet as a Binary-State System. The following topologies are considered: (a) a homogenous irredundant drone fleet, (b) a homogenous hot stable redundant drone fleet, (c) a heterogeneous irredundant drone fleet, and (d) a heterogeneous hot stable redundant drone fleet. For the listed topologies, reliability estimates were obtained as a function of the number of primary and redundant UAVs.

Keywords: UAVs, Reliability, Binary-State System, Importance analysis, Structure Function, Availability.

1 Introduction

A UAV is a relatively new technology used for monitoring, search, communication, cargo delivery, etc. [1] The use of UAVs in practice is justified by their relatively low cost [2], the availability of devices on the market [3], the possibility of use in hard-to-reach places [4], and the possibility of adaptation to special tasks [5] and relatively simple control methods [6].

These advantages provide significant potential for UAV applications ranging from the entertainment industry to geological exploration [7-10]. According to estimates, the UAV market will reach $127 billion, of which 36% will be used for infrastructure, 26% for agriculture, 10% for transportation, etc.[11] (see **Chyba! Nenašiel sa žiaden zdroj odkazov.**).

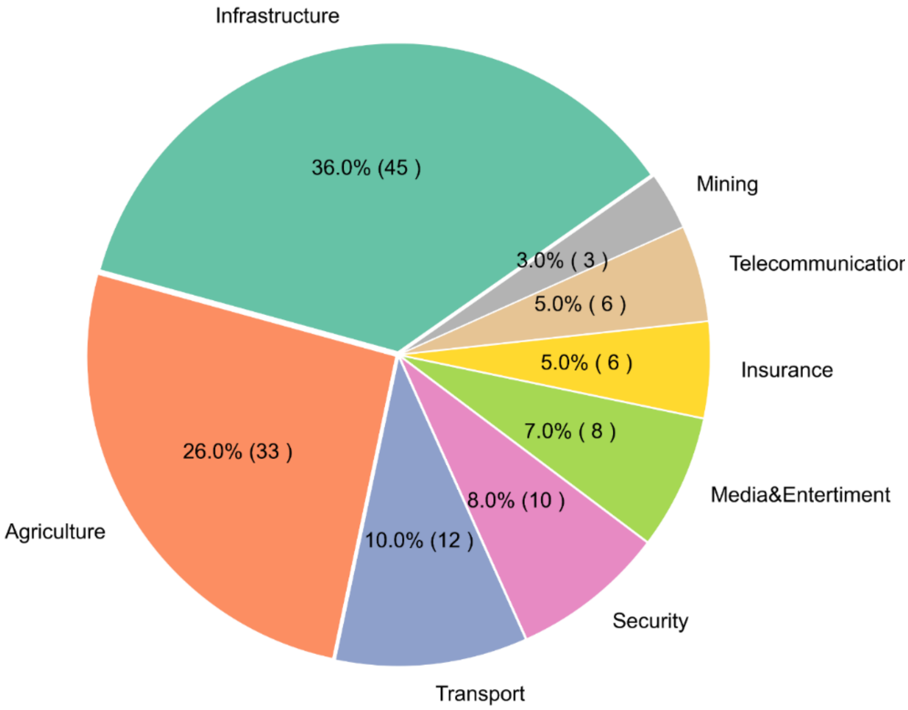

Fig. 1. Future market of UAVs.

Practical applications of UAVs are considered in close connection with artificial intelligence technologies. In essence, there is a fusion of intelligent data processing and UAVs. A set of methods and means of Intelligent Unmanned Aerial Vehicle Technology (IUAVT) is being formed) [12]. There are three main categories of limitations that limit the widespread use of technology in various sectors of the economy [10]:

1. Technical. Limitation of battery capacity, flight time, payload, sensor sensitivity, dependence on weather conditions, limitations in computing power on board, etc.;
2. Legal. The impossibility of some use options within the city limits and restrictions on the use of UAVs weighing more than 250 grams [13];
3. Software and algorithmic.

The third group of limitations is caused by the relatively low computing power of the onboard computer, and the insufficient development of algorithms related to the main applications of UAVs, including flight planning. Flight planning is defined by the mission performed by one or more UAVs. Among such tasks performed during the flight, the literature mentions: search operations, routing for a set of locations, area coverage, data collection and recharging in a wireless sensor network (WSN), allocation of communication channels and computing power for mobile devices, and the operational aspects of a self-organizing drone network [5]. However, UAVs and ground-based communication and control systems as technical devices are not reliable. The limited reliability of technical means should be taken into account in the planning process, especially in those tasks that are critically time-dependent (search for victims, application of fertilizers and herbicides, organization of communication in emergency areas, etc.).

In this paper, we consider approaches to estimating the reliability of drone fleets using the Binary-State System representation of the fleet.

The paper consists of the following sections:

Related works section, analyzes the current state of research on UAV applications, reliability assessment methods.

The third section discusses the methods for analyzing drone fleet reliability and the results.

The fourth section describe the fleet structure and functions of unmanned aerial vehicles.

Fifth section consist on analysis of the availability of UAV fleets based on a structure function.

In the sixth part analyzing and evaluating the impact of components' failures on a system.

In the last section, conclusion, we summarize the need to calculate UAV fleet reliability when executing missions of different types and particular responsibility. In this paper, this gap is partially filled. Methods of evaluation are described in the paper.

2 Related works

The IUAVT is used for a variety of tasks, including:

1. Monitoring:

- For mapping, which usually requires overlapping images to produce a quality map [14, 15];
- Monitoring along a predetermined route (structures [16], technical facilities [17] pipelines [18,19];
- Monitoring using special equipment, such as thermal and multispectral cameras, gamma spectrometers, aeromagnetic sensors etc., when it is necessary to take into account the peculiarities of the equipment during missions [20,21];
- Monitoring-inspection of casualty areas during emergencies [22-24];
- Traffic monitoring [25];
- Wildlife monitoring [15,26].

2. Detection and identification [27,28]:

- conditions of structures, harvested crops, animals [29];
- violations of laws, such as hunting [30];
- air or aquatic environment, periodically at predetermined points in time [31,32,28].

3. Search:

- Protecting and Searching for Animals [33,34];
- Injured people [35,36];
- Minerals [37,38];
- etc.

4. Delivery [39] and transportation of cargo, including oversized cargo on suspension [40].
5. Organization of communications:

- Collection of data from installed sensors: in precision farming [41], wireless sensor networks [42]:
- In natural disaster areas [43-45].

Figure 2 shows the distribution of publications on UAV applications.

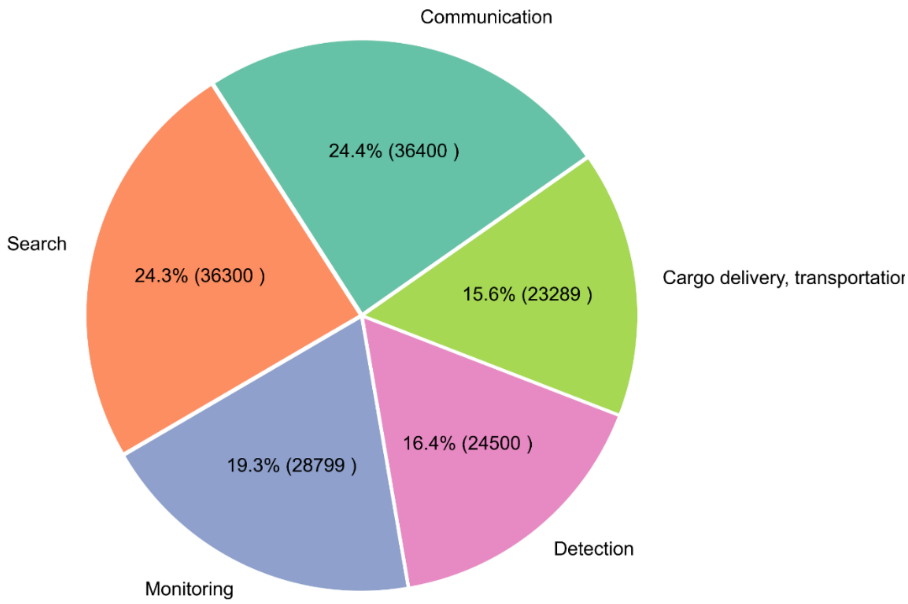

Fig. 2. Number of publications according to Google Scholar since 2018.

The effective applications of UAVs in the implementation of the discussed problems are caused by some characteristics and properties of itself UAVs. One of the important properties of UAVs application is the definition of the optimal coverage path planning

(CPP) [46-48]. There are two modifications of this problem: CPP1 - without influence on the surface analyzed; CPP2 - with influence on the surface coated.

Another important property of UAVs is reliability, which allows determining the conditions of UAVs' functioning performance at the specified level [49]. The reliability analysis or reliability engineering is a knowledge domain, which includes many approaches, methods, and algorithms for reliability evaluation and risk assessment of complex systems. The choice and application of methods for reliability analysis in every specified case depend on a system structure, its type, and area of applications. UAVs are complex systems from point of view of reliability analysis. In the study [50] the classification of UAV reliability analysis depending on different parameters has been introduced. This classification is presented in form of a parameters matrix, which takes into consideration such aspects as the number of drones in exploitations, homogenous or heterogeneous structure of UAVs' fleet, and type redundancy in drone fleets. This classification matrix of UAV's fleet reliability is shown in Table 1. In this matrix types of UAVs' structures as a single drone, UAVs' fleet, and UAVs' multi-fleet are considered. These structures can implement one function (it is indicated by "1") or can be multi-functions (this parameter is indicated as MF). The UAVs' fleet and UAVs' multi-fleet can be formed by homogenous drones or can be heterogeneous, which is indicated by "Y" in the column "Heterogeneous" and the symbol "N" in this column specifies a homogenous type of drone fleet. A single UAV or UAV's fleet can be represented by two mathematical models: *Binary-State System* (BSS) or *Multi-State System* (MSS). A BSS is a mathematical model which has two states in the system functioning and two states of components in the mathematical representation. A MSS is a mathematical model, which allows consideration in the mathematical representation of more than two states for a system functioning and the system's components states. MSS permits to describe and analyze a system in more detail: it is possible to analyze not the system failure only but the system degradation too. However, the methods for MSS reliability analysis request higher computational resources [51]. There are some investigations of a MSS used for reliability analysis of UAVs [50, 52, 53]. But most of the studies in UAVs' reliability use a BSS for the mathematical representation of the investigated system [50, 54]. Besides the specified parameters of UAV or UAV's fleet, the specifics of reliability should be taken into consideration too. For UAVs, the first should be to consider the redundancy of the system. Typically, two types of redundancy are investigated: active redundancy and standby redundancy [55]. A standby redundancy can be hot, cold, and warm standby sparing [56]. The use of every one of these types of redundancy is caused by the request for the time or energy resources of the specified application of UAVs. The cold redundancy is typically used in the system if it is critical for energy consumption: the spare component is started functioning only when the worked component fails. Hot standby sparing is used as a failover mechanism to provide the reliability of a system, where the recovery time is critical. The mathematical model for this type of redundancy is equal to active redundancy if the switching delays and failures are not taken into consideration. Warm standby sparing compromises the energy consumption and the recovery time. The spare components are partially powered up when the primary component is operational and it is fully powered up only after the primary component fails.

Table 1. Matrix of UAVs' Fleet Reliability Assessment Parameters from [50].

UAV/UAVs' Fleets					**Reliability**		
Type	**Parameters**			**Irredundant**	**Redundant**		
	Functions	**Mat. Model**	**Hetero-geneous**		**Hot standby**	**Cold standby**	**Warm standby**
Singl UAV	1	BSS	–				
		MSS	–				
	MF	BSS	–				
		MSS	–				
UAVs' flee	1	BSS	Y	x	x		
			N	x	x		
		MSS	Y				
			N				
	MF	BSS	Y	x	x		
			N	x	x		
		MSS	Y				
			N				
UAVs' Multy-fleet	MF	BSS	Y				
			N				
		MSS	Y				
			N				

The methods of reliability analysis depend on the structure of the system. The methods for reliability evaluation of a single drone differ from the methods of UAVs' fleets. According to a study [50, 53] most often used structure for UAVs is the UAV's fleet. A UAVs' multi-fleet is not often used because needs many resources (energy, financial, etc.). A UAV's fleet allows archive good results in such problems as monitoring [57], transportation [58], and agriculture [59]. Therefore, this structure is considered in the paper. The parameter of fleet functions has some correlation with the homogenous and heterogeneous types of UAVs' fleet. There are problems in which these parameters cannot be joined and should be considered as two independent parameters. In this study, we assume the correlation of these parameters: the homogenous fleet implements one function and the heterogeneous fleet can have some functions for the implementation and every fleet drone is with one function. Typically, the methods for the reliability analysis of homogenous [60] and heterogeneous [61] fleets are different. In this paper, we propose a new method of the UAVs' fleet reliability evaluation, which can be used, for both homogenous and heterogeneous fleets. From point of view of redundancy, this method can be applied for irredundant drone fleets or fleets with hot redundancy. The hot redundancy is considered because in most applications of UAVs' fleet the time is critical for the spare drone start.

3 Method and results

The proposed method is based on BSS in mathematical representation of the UAVs' fleet. In particular, the structure function based method is developed. The structure function as mathematical model in reliability analysis is one of simplest mathematical representation [62, 63]. This function maps the set of system components' states to one of the system state. In case of the BSS this function agrees with a Boolean function. Let us consider a system of *n* components (drones). The i-th drone functioning is denoted by variable x_i $(i = 1, \dots, n)$ where $x_i = 1$ if the drone is functioning state and $x_i = 0$ if it fails. The system state (its reliability) depends on the states of the components (drones). This depending is defined by the structure function [62,63]:

$$\phi(x_1, \dots, x_n) = \phi(\boldsymbol{x}): \ \{0,1\}^n \to \{0,1\}, (1)$$

where $\boldsymbol{x} = (x_1, \dots, x_n)$ is a vctor of the system components states (state vector); $\phi(\boldsymbol{x}) = 1$ if the system is functioning and $\phi(\boldsymbol{x}) = 0$ if the system is failure.

A UAVs fleet is a coherent system. It means that all component are (a) relevant for the system ($\phi(1_i, \boldsymbol{x}) \neq \phi(0_i, \boldsymbol{x})$ for some state vectors) and (b) failure of any component cannot result the improvement in the system functioning ($\phi(1_i, \boldsymbol{x}) \geq \phi(0_i, \boldsymbol{x})$ for any component), where $\phi(1_i, \boldsymbol{x}) = \phi(x_1, \dots, x_{i-1}, 1, x_{i+1}, \dots, x_n)$ and $\phi(0_i, \boldsymbol{x}) = \phi(x_1, \dots, x_{i-1}, 0, x_{i+1}, \dots, x_n)$. The structure function (1) for a coherent system is monotonically non-decreasing [62].

The structure function advantages are possibility of the representation of a system of any structural complexity and simplify methods for reliability evaluation. The disadvantage of this mathematical model is large dimension of system of many components: the structure function dimension is exponential increase depending on the number of the system components [62]. For the decision of this difficulty in reliability analysis, some approaches have been proposed. One of them is use of Binary-Decision Diagram (BDD), which has been developed in Boolean Algebra [64] and are effective for the processing of the function of large dimensional [63]. The alternative approach is based on the structure function representation in form of survival signature [65].

4 Structure function of UAV's fleet

Need to note that the reliability of the system is a complex characteristic, which includes some indices and measures. The reliability analysis of a UAV's fleet drone supposes the calculation of some indices and measures. The drone fleet reliability in the stationary state is studied in this paper. The assumption about equivalent properties of multi-functions and heterogeneous in this study takes into consideration. It allows us to consider the mathematical model in form of the structure function (1). The structure function should be defined for the fleet:

- Homogenous irredundant drone fleet (see Fig. 3 (a));
- Homogenous hot stable redundant drone fleet (see Fig. 3 (b));
- Heterogeneous irredundant drone fleet (see Fig. 3(c));
- Heterogeneous hot stable redundant drone fleet (see Fig. 3 (d)).

These fleets can include a Main Drone Fleet (MDF) for the implementation of the objective action, a Reverse Drone Fleet (RDF) for the support of the functioning state of a MDF and Control Unit (CU) for the coordination of drones actions.

One of the possible ways to construct structure function is based on the application of typical structures of systems, which are series, parallel and k-out-of-n systems. There are two definitions of k-out-of-n system. A k-out-of-n:G is functioning if k or more of n components are in the working states. A k-out-of-n:F is a system that fails if at least k components are failed. In this study k-out-of-n:G type is used only, therefore the nomination k-out-of-n will be used for this system. It is well known that the system k-out-of-n is a generalization of two other typical structures: 1-out-of-n corresponds to a parallel system and n-out-of-n agrees with a series system. Therefore, the drone fleet functioning is presented and studied as k-out-of-n system in this paper.

A homogenous irredundant drone fleet with decentral control (see Fig. 3 (a)) can be presented by two topologies. One of them has the distribution control and the other topology includes the central CU. A decentral control topology is interpreted as the n-out-of-n system or the series system with the structure function:

$$\phi(\boldsymbol{x}) = \wedge_{w=1}^{n} x_w \,, (2)$$

where $\wedge_{w=1}^{s}$ is the symbol of Boolean operation AND for w variables.

The structure function of a homogenous irredundant drone fleet with the central CU (see Fig. 3 (a)) can be defined as the series system of the MDF and CU, where drone fleet is the series system:

$$\phi(\boldsymbol{x}) = (\wedge_{w=1}^{n-1} x_w) \ \wedge x_n = \wedge_{w=1}^{n} x_w \,, (3)$$

where the variables from x_1 to x_{n-1} are represent the states of the drones of the MDF and variable x_n represents the states of the CU.

A homogenous hot stable redundant drone fleet can be presented by two topologies too (see Fig. 3 (b)). Similar to the previous structure of UAV's fleet, this structure can have distribution control and the central CU for fleet control. The hot stable redundant can be presented as the k-out-of-n. According to [66] the structure function of the k-out-of-n system and analysis of its reliability can be based on an analysis of minimal paths set. The structure function of such a system is defined as the unit of minimal paths:

$$\phi(\boldsymbol{x}) = \vee_{Q_k} \wedge_{w=1}^{k} x_{i_w} \,, (4)$$

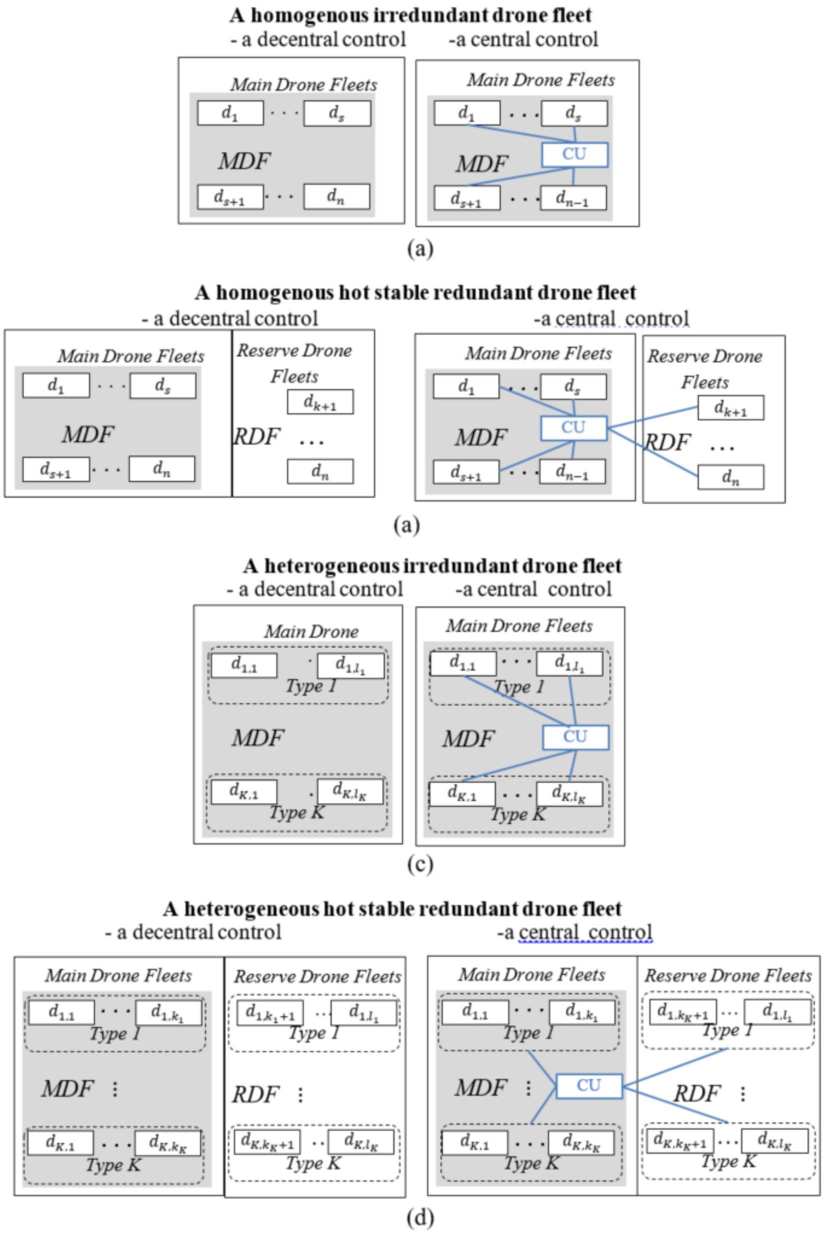

Fig. 3. The topologies of (a) a homogenous irredundant drone fleet, (b) a homogenous hot stable redundant drone fleet, (c) a heterogeneous irredundant drone fleet, and (d) a heterogeneous hot stable redundant drone fleet.

where $\vee_{w=1}^{k}$ is the symbol of Boolean operation OR for k variables; the k variables x_{i_s} (s = 1, …, k) represent the states of the drones which are formed by the minimal paths in the topology of k-out-of-n system and the number of the paths Q_k is defined as:

$$Q_k = \binom{n}{k} = \frac{n!}{(n-k)!k!}, \ (5)$$

The structure function of k-out-of-n system (3) is formed by the Q_k implicants and each implicant has k literals.

The structure function of a homogenous hot stable redundant drone fleet with the central CU in Fig. 3 (b) can be defined as the series system of the MDF and CU, where the drone fleet is the k-out-of-n system:

$$\phi(\boldsymbol{x}) = \left(\vee_{Q_k} \wedge_{w=1}^{k} x_{i_w}\right) \ \wedge x_n \, , (6)$$

where the variables from x_1 to x_{n-1} represent the states of the drones of the MDF and RDF and variable x_n represents the states of the CU.

A heterogeneous irredundant drone fleet with decentral control (see Fig. 3 (c)) is formed of UAVs of K types. Drones of every type of irredundant drone fleet are formed a series system. All of these K series systems must be working for the work of a heterogeneous irredundant drone fleet:

$$\phi(\boldsymbol{x}) = \left(\wedge_{r=1}^{K} \wedge_{w=1}^{l_K} x_{r,w}\right) \ = \wedge_{w=1}^{n} x_w \, , (7)$$

where the number of variables $x_{r,w}$ for all possible values of the parameters r and w is equal to the number n; l_r is the number of UAVs of type r (r = 1, …, K).

A heterogeneous irredundant drone fleet with decentral control from point of view of the reliability analysis is a series system that can be worked if all drones of all types are functioning. A similar topology has a heterogeneous irredundant drone fleet with central control (see Fig. 3 (c)), which is a series system too with the structure function:

$$\phi(\boldsymbol{x}) = \left(\wedge_{r=1}^{K} \wedge_{w=1}^{l_K} x_{r,w}\right) \ \wedge x_n = \wedge_{w=1}^{n} x_w \, , (8)$$

where the variables $x_{r,w}$ represent states of drones of MDF and for all possible values of the parameters r and w the number of these variables is equal to the number n-1; the variable x_n is used for the representation of CU states.

A heterogeneous hot stable redundant drone fleet with distributed control (see Fig. 3 (d)) is formed by UAVs of K types and every one of these types of drones is the k-out-of-n system with the structure function which is similar to (6). The working state of the fleet is possible if each drone' type implements specified activity. The structure function of this type of heterogeneous drone is a series system of K components which are kr-out-of-lr systems:

$$\phi(\boldsymbol{x}) = \wedge_{r=1}^{K}\left(\vee_{Q_r} \wedge_{w=1}^{k_r} x_{r,i_w}\right) , (9)$$

where Q_r is the number of minimal paths for each type of UAVs which is computed according to (5) and k_r is the number of minimum required working drones for type r (r = 1, …, K).

A heterogeneous hot stable redundant drone fleet with the central CU (see Fig. 3 (d)) in reliability analysis point of view is formed by K kr-out-of-lr systems which are interconnected in series and connected in series with the control element:

$$(\boldsymbol{x}) = \left(\wedge_{r=1}^{K}\left(\vee_{Q_r} \wedge_{w=1}^{k_r} x_{r,i_w}\right)\right) \wedge x_n \ , (10)$$

The structure functions (2) – (4) and (6) – (10) are defined for homogeneous and heterogeneous UAVs' fleets that can be irredundant or hot stable redundant. The introduced structure function for all types of irredundant fleets (2), (3), (7), and (8) are equal and are presented as series topology. Therefore, the reliability analysis for these fleets can be implemented as for one series system. Hot stable redundant drone fleets have different structure functions (4), (6), (9), and (10) and for every one of them should be proposed reliability evaluation.

5 Availability of UAV's fleet defined based on a structure function

The reliability analysis of the system based on the structure function is studied well [62, 66]. The system availability is defined depending on the probabilities of the system components functioning state, which is defined as:

$$p_i = \Pr\{x_i = 1\}, (11)$$

and the probabilities of the system components failure, which are:

$$q_i = 1 - p_i = \Pr\{x_i = 0\}, (12)$$

The system probability to be in the functioning state is system availability [62, 66]. Because the UAV's fleet is a coherent system than the availability can be defined as:

$$A = \Pr\{\phi(\boldsymbol{x}) = 1\}, (13)$$

and the system unavailability is defined as:

$$U = 1 - A = \Pr\{\phi(\boldsymbol{x}) = 0\}. (14)$$

As the first, the series structures of the irredundant fleets are considered. A homogenous irredundant drone fleet with decentral control (Fig. 3 (a)) is formed for drones that have equal characteristics, in particular, the probability of the drone to be in a working state: $p_i = p_j = p$ for $i \neq j$. It allows us to define this fleet availability A_{HoID} according to (2) and (13) as :

$$A_{HoID} = \Pr\left\{\bigwedge_{w=1}^{n} x_w\right\} = \prod_{w=1}^{n} p_w = p^n, (15)$$

The availability of a homogenous irredundant drone fleet with central CU (see Fig. 3 (a)) A_{HoIC} is similar to the availability of a homogenous irredundant drone fleet with decentral control. But the definition of this availability should take into consideration of the probability of functioning of the CU p_n:

$$A_{HoIC} = \Pr\{\,(\wedge_{w=1}^{n-1} x_w)\ \ \wedge x_n\} = (\prod_{w=1}^{n-1} p_w) \cdot p_n = p^{n-1} \cdot p_n, \ (16)$$

where p is the probability of the working state of UAVs of MDF and p_n is the probability of CU being in the working state.

The definitions of availability (15) and (16) for irredundant homogenous UAV fleets allow us to provide the analysis and comparison of the availability of these homogenous fleets (see Fig.4). The curves of availabilities in Fig. 4 reflect the average values of availabilities of these two fleets. They have been computed for the probabilities of UAV and CU, which change from 0.600 to 0.999 accordingly and the probability of CU functioning is more than the probability of UAV working state. According to this study, a homogenous irredundant drone fleet with central CU has the best availability for the fleet which consists of less than 12 UAVs.

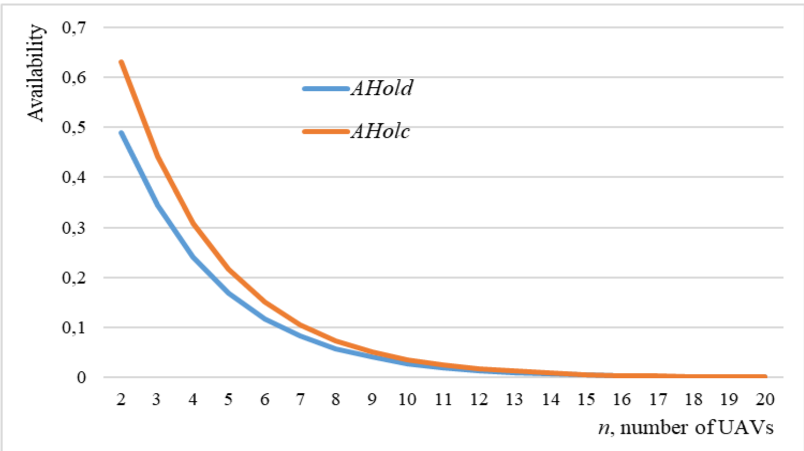

Fig. 4. The availabilities of homogenous irredundant UAV fleets.

The availability of heterogeneous irredundant fleets should take account of some types of UAVs. The probability of UAV of type r functioning is denoted as p_r, where r = 1, …, K, and lr is the number of UAVs of type r. The availability of a heterogeneous irredundant drone fleet with decentral control (see Fig. 3 (c)) A_{HeID} according to (7) and (13) is:

$$A_{HeID} = \Pr\{\,(\wedge_{r=1}^{K} \wedge_{w=1}^{l_K} x_{r,w})\} = \prod_{r=1}^{K} p_r^{l_r}\ , (17)$$

The availability of a heterogeneous irredundant drone fleet with central CU (see Fig. 3 (c)) A_{HeIC} according to (8) and (13) and the assumption of the probability p_n of the working state of CU is:

$$A_{HeIC} = \Pr\{ \left(\wedge_{r=1}^{K} \wedge_{w=1}^{l_K} x_{r,w}\right) \ \wedge x_n\} = \left(\prod_{r=1}^{K} p_r^{l_r}\right) \cdot p_n, \ (18)$$

The analysis of the availabilities of heterogeneous irredundant drone fleets is shown in Fig.5. The curves of availability have been computed for the different number of drone types and the number of drones in the fleet. The number of drone types is taken into account too: from 2 to 5 types have been evaluated for these fleets of 20 drones. This experimental investigation shows that the increase in the number of UAV types has a threshold and the larger number of drone types has no positive impact on fleets' availability. The best solution for a fleet that consists of less than 7 drones is two types.

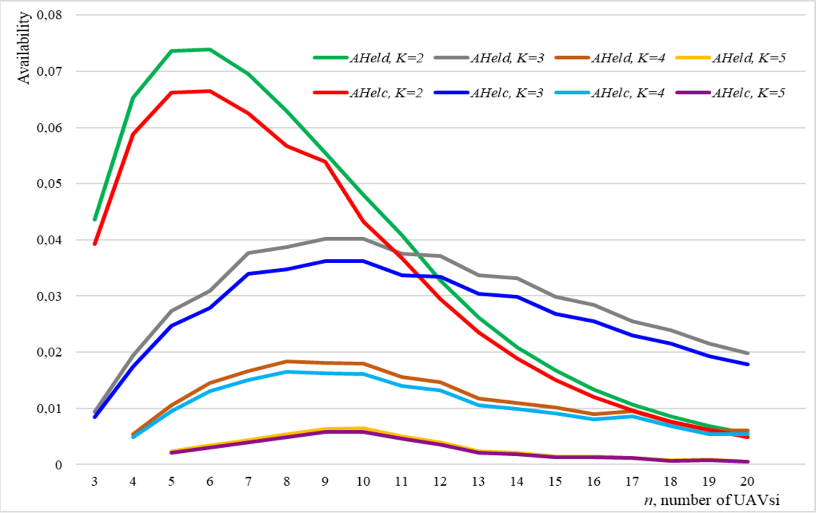

Fig. 5. The availabilities of heterogeneous irredundant UAV fleets.

The background topology of hot stable redundant drone fleets is the k-out-of-n system. A homogenous hot stable redundant drone fleet with decentral control (see Fig. 3 (b)) is k-out-of-n system with identical components. The availability of this system, for example, is defined in [66, 67] and for this UAV's fleet is:

$$A_{HoRD} = \Pr\left\{\bigvee_{Q_k} \bigwedge_{w=1}^{k} x_{i_w}\right\} = \sum_{s=k}^{n} \binom{n}{s} \cdot p^s \cdot q^{n-s}, (19)$$

The availability of a homogenous hot stable redundant drone fleet according to (19) depends on the number of part of working drones' k (see Fig.6). Therefore, the analysis of this fleet availability is provided depending on the number of drones in the fleet and the specified number of working drones. This analysis shows that the increase in the number of specified working drones for the fixed number of drones in the fleet results in the deterioration in reliability. Similar to the previous experiments, Figure 4 shows the average dependences, and the studies were performed for a set of probabilities of the operational state of drones from 0.6 to 0.0999.

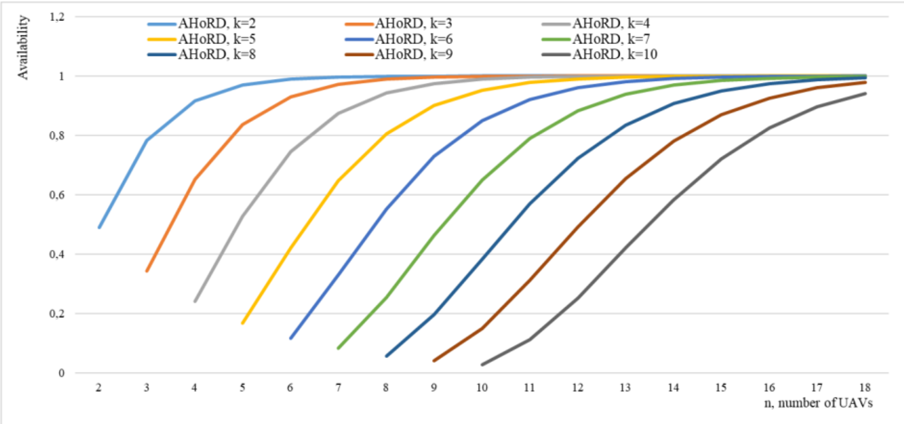

Fig. 6. The availability of homogenous hot stable redundant drone fleet with decentral control.

The structure function of a homogenous hot stable redundant drone fleet with central CU in Fig. 3 (b) is defined by (1.5) and besides k-out-of-n system includes the component CU, which is in series. Therefore, the availability of this fleet is:

$$A_{HoRC} = \Pr\left\{\left(\bigvee_{Q_k}\bigwedge_{w=1}^{k} x_{i_w}\right) \bigwedge x_n ,\right\} = \left(\sum_{s=k}^{n-1}\binom{n-1}{s}\cdot p^s\cdot q^{n-s}\right)\cdot p_n, \qquad (20)$$

The availability of a homogenous hot stable redundant drone fleet with the central CU is similar to the availability of a homogenous hot stable redundant drone fleet with decentral control. The change of the fleet control from decentralized to centralized leads to a slight decrease in the reliability of this fleet with central CU (see Fig.7).

A heterogeneous hot stable redundant drone fleet with distributed control (see Fig. 3 (d)) consists of drones of types and has structure function (9). The availability of this fleet according to (13) and the definition of the availability of the k-out-of-n system in [66, 67] is computed as:

$$A_{HeRD} = \Pr\left\{\bigwedge_{r=1}^{K}\left(\bigvee_{Q_r}\bigwedge_{w=1}^{k_r} x_{r,i_w}\right)\right\} = \prod_{r}^{K}\sum_{s=k_r}^{l_r}\binom{l_r}{s}\cdot p_r^s\cdot q_r^{l_r-s}. (21)$$

The evaluation of the average availability of a heterogeneous hot stable redundant drone fleet with distributed control is in Fig.8, which shows that the increase in the number of UAVs in the fleet leads to a decrease in its availability. Therefore, the heterogeneity of the fleet increasing without a due need is unjustified from the point of view of availability.

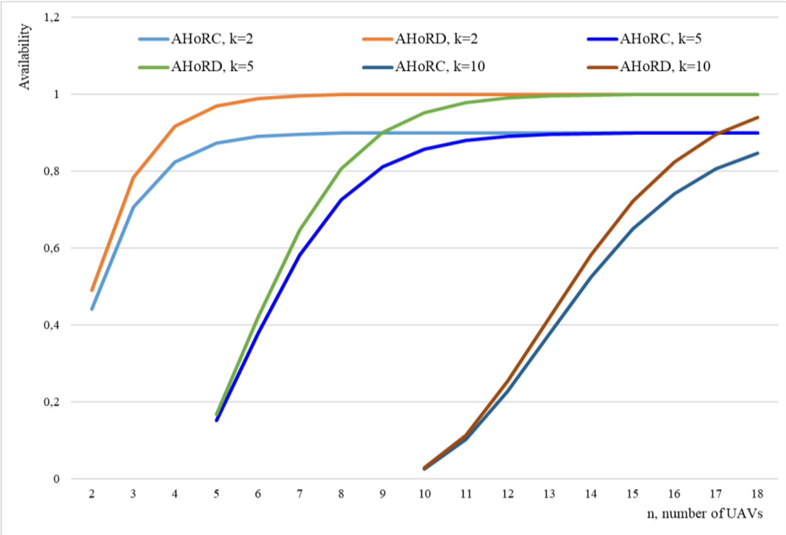

Fig. 7. The comparison of availability of a homogenous hot stable redundant drone fleets with decentral control and central CU.

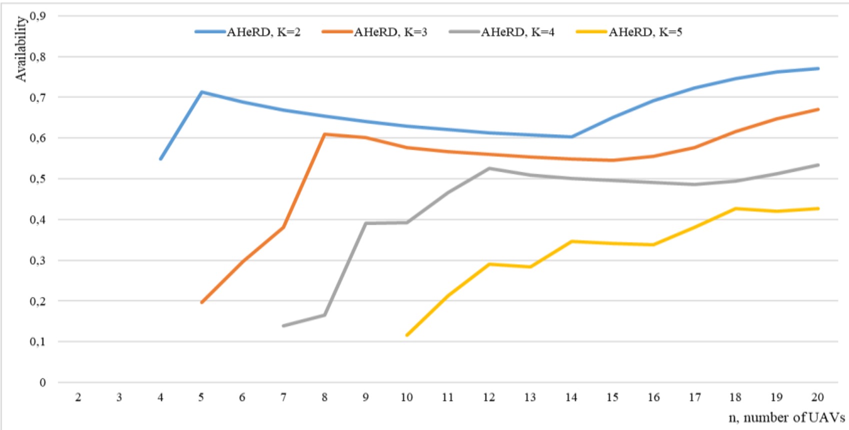

Fig. 8. The availability of a heterogeneous hot stable redundant drone fleet with distributed control.

The availability of a heterogeneous hot stable redundant drone fleet with central CU (see Fig. 3 (d)) A_{HeRC} is defined in a similar way:

$$A_{HeRD} = \Pr\left\{\left(\bigwedge_{r=1}^{K}\left(\bigvee_{Q_r}\bigwedge_{w=1}^{k_r} x_{r,i_w}\right)\right)\bigwedge x_n\right\} = \left(\prod_{r}^{K}\sum_{s=k_r}^{l_r}\binom{l_r}{s}\cdot p_r^s\cdot q_r^{l_r-s}\right) \cdot p_n., (22)$$

The use of a central CU for the control in a heterogeneous hot stable redundant drone fleet causes the availability decreasing (see Fig.9). The availability of a heterogeneous hot stable redundant drone fleet with central CU is similar to the availability of a fleet with decentral control.

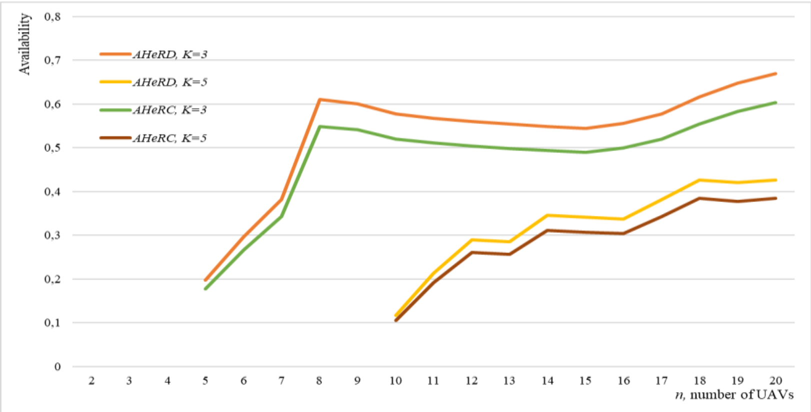

Fig. 9. The comparison of availability of a heterogeneous hot stable redundant drone fleets with decentral control and central CU.

The general evaluation of availabilities of fleets structures shows that the best structure in point of view of the availability is homogenous hot stable redundant drone fleet with decentral control. But un the practical application should be taken into account the technical complication for the implementation of the decentral control of fleet, which can cause the decreasing of the UAV reliability properties [68]. Therefore, the alternative can be homogenous hot stable redundant drone fleet with central CU.

6 Importance analysis of UAV fleets

The availability of the different structures of UAV fleets allows for evaluating a fleet as the system as a whole. But often system exploitation needs to have quantification of the influence of some components' failure on system reliability or availability. For example, quantification of the influence of failure of different drone types on a fleet functioning can be useful for the maintenance of a UAV's fleet. The analysis and evaluation of the influence of specified components functioning or their failure on a system is part of the reliability analysis which is known as importance analysis [69]. Methods of importance analysis allow computing of Importance Measures (IM), which quantify the impact of specified system components on a system failure or performance. There are different types of IMs that quantify various aspects of a system failure or operation in case of failure or recovery of a failed component. Most of them depend on the probability of the component being in working or failed states and they can be computed based on data, which is collected in system exploitation. Structural Importance (SI) is one of IMs which is based on the topological properties of the system and can be used in the step of the system development. Where the information about probabilities of components failure is absent. The SI evaluates the probability of the system failure depending on specified component fails and it is computed as a relative number of state vectors at which a failure of the i-th system component causes a system failure [69]. This definition supposes the identification of situations in which a failure of a fixed component causes the system failure. In the case of a drone fleet analysis, this measure allows us to evaluate the probability of a fleet failure if a specified drone or CU fail.

There are different algorithms, which allow the computation of the SI [67, 69]. One of the known algorithms is based on the application of Direct Partial Boolean Derivatives (DPBD) [63]. According to the definition of this derivative in Boolean algebra, DPLD with respect of the i-th variable allows defining the sets of a Boolean function variables values for which the change of the i-th variable value results in the change of the Boolean function value [70, 71]. In reliability analysis DPLD of the structure function (1) allows the definition of the system component states (state vectors) for which the change of the i-th component state results in the change of the system state [63]:

$$\frac{\partial\phi(j \to \tilde{j})}{\partial x_i(s \to \tilde{s})} = \begin{cases} 1, if\ \phi(s, \boldsymbol{x}) = j\ and\ \ \phi(\tilde{s}, \boldsymbol{x}\ ) = \tilde{j}) \\ 0, other \end{cases}, (23)$$

where s, $\tilde{s}$, j, $\tilde{j}$ $\in$\{0,1\} and $s \neq \tilde{s}$, $j \neq \tilde{j}$; the change of the variable value from s to $\tilde{s}$ and the function value from j to $\tilde{j}$ is defined by the symbol $\rightarrow$.

In this paper, an unrecoverable fleet is considered, therefore the SI for the system failure depending on its components failure is used in the analysis. In this case, the DPLD is defined as:

$$\frac{\partial\phi(1\to0)}{\partial x_i(1\to0)} = \begin{cases} 1, if\ \phi(1, \boldsymbol{x}) = 1\ and\ \ \phi(0, \boldsymbol{x}\ ) = 0) \\ 0, other \end{cases} = \overline{\phi(0_\imath, \boldsymbol{x})} \wedge \phi(1_i, \boldsymbol{x}),\ (24)$$

The definitions of the SI and DPLD (1.23) have an obvious correlation, which can be used for the SI computation based on DPLD [63]:

$$\mathrm{SI}_i = \mathrm{TD}\left(\frac{\partial\phi(1 \to 0)}{\partial x_i(1 \to 0)}\right) = \frac{\rho}{2^{n-1}}, (25)$$

where TD(.) is the truth density of the argument and this value agrees with the relative number of vectors for which the argument takes a nonzero value; ρ is the number of the system states for which the i-th system component failure causes the system failure or it is non-zero values of the DPBD (24)

The SIs for considered structures of drone fleets are computed based on their structure function definitions (2) – (4), (6) – (10) according to (25). the computation of SIs of a drone of homogenous and heterogeneous irredundant drone fleets (Table 2) are computed as SI of a series system. The SIs of CU in irredundant drone fleets with central CU are computed based on a series system too. The definition of SI of UAV in a homogenous hot stable redundant drone fleet with decentral control is SI of k-out-of-n system defined in [72]. In the study [73] the chain rule for the calculation of DPBD of complex structure function represents a system has been introduced. In the study [73], a complex system is interpreted as a system that can be decomposed to a set of based structures as series, parallel, and k-out-of-n. The chain rule is used for the definition of SIs of a drone and CU for a homogenous hot stable redundant drone fleet with central CU in Table 2. Based on the chain rule the SIs of a drone in heterogeneous hot stable redundant drone fleets with decentral control and central CU have been defined too.

Table 2. The SIs of the components of drone fleets.

A fleet structure	**SI**	
	the i-th drone	CU
Homogenous irredundant drone fleet with distributed control	$\frac{1}{2^{n-1}}$	
Homogenous irredundant drone fleet with central CU	$\frac{1}{2^{n-1}}$	$\frac{1}{2^{n-1}}$
Homogenous hot stable redundant drone fleet with decentral control	$\frac{(n-1)!}{2^{n-1}\cdot(n-k)!\cdot(k-1)!}$	
Homogenous hot stable redundant drone fleet with central CU	$\frac{(n-2)!}{2^{n-1}\cdot(n-1-k)!\cdot(k-1)!}$	$\frac{(n-2)!}{2^{n-2}\cdot(n-1-k)!\cdot(k-1)!}$
Heterogeneous irredundant drone fleet with decentral control	$\frac{1}{2^{n-1}}$	
Heterogeneous irredundant drone fleet with central CU	$\frac{1}{2^{n-1}}$	$\frac{1}{2^{n-1}}$
Heterogeneous hot stable redundant drone fleet with decentral control	$\left(\prod_{r}^{K}\sum_{s=k_r}^{l_r}\frac{(l_r-1)!}{2^{l_r-1}\cdot(l_r-k_r)!\cdot(k_r-1)!}\right)$	
Heterogeneous hot stable redundant drone fleet with central CU	$\left(\prod_{r}^{K}\sum_{s=k_r}^{l_r}\frac{(l_r-1)!}{2^{l_r-1}\cdot(l_r-k_r)!\cdot(k_r-1)!}\right)$	$\left(\prod_{r}^{K}\sum_{s=k_r}^{l_{r-1}}\frac{(l_r-2)!}{2^{l_r-2}\cdot(l_r-k_r-1)!\cdot(k_r-1)!}\right)$

7 Conclusion

UAVs are widely used for monitoring, search, communications, etc. A significant number of scientific works are devoted to solving the problems of mission optimization for solving the problems of territory coverage, selection of the optimal route under various conditions of application of individual UAVs and groups of vehicles. Much less attention is paid to the reliability analysis of missions by groups (fleets) of UAVs.

Calculation of UAV fleet reliability is necessary to assess the required degree of fleet redundancy in the execution of missions of different types and especially high-responsibility ones. This paper partially closes this gap. The paper describes evaluation methods.

Availability of UAV’s fleet based on a structure function. In this paper, a new method for the reliability estimation of drone fleet is proposed. This method is based on the fleet representation by the structure function (1). The structure function is one of the mathematical models in reliability engineering which allows the representation of a system of any structural complexity. It is confirmed by a drone fleet analysis. The proposed method can be used for the analysis of homogenous and heterogeneous fleets which have different types of control. The formulas for the availability calculation for 8 types of drone fleets are defined (15) – (22). These definitions of availability can be used for the simplified evaluation of the fleets of different types (structures). The proposed definitions of availability for different types of drone fleets allow for the providing of fleets’ reliability analysis with reduced computational complexity. In addition, these definitions allow us to evaluate the availability behavior of the considered types of UAV’s fleet and propose recommendations for their structure (numbers of drones, number of reserved drones, number of drones’ types). These recommendations can be formed according to the curves of availabilities changes depending on the structural parameters of fleets that are shown in the diagrams in Fig. 4 – 9. The influence of a drone breaks down to the fleet failure is studied through the importance analysis approach. The measures of SIs are defined in Table 2 for considered structures of fleets. In the future investigation the analysis of these measures will be implemented in more detail and other IMs, for example, Birnbaum Importance will be studied too.

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References

1. Shakhatreh, H., Sawalmeh, A.H., Al-Fuqaha, A., Dou, Z., Almaita, E., Khalil, I., Othman, N.S., Khreishah, A., Guizani, M.: Unmanned Aerial Vehicles (uavs): A survey on civil applications and key research challenges. IEEE Access. 7, 48572–48634 (2019).
2. Denora, M., Fiorentini, M., Zenobi, S., Deligios, P.A., Orsini, R., Ledda, L., Perniola, M.: Validation of rapid and low-cost approach for the delineation of zone management based on machine learning algorithms. Agronomy. 12, 183 (2022).
3. Tsolakis, N., Harrington, T.S., Srai, J.S.: Digital Supply Network Design: A circular economy 4.0 decision-making system for real-world challenges. Production Planning & Control. 1–26 (2021).
4. Giordan, D., Adams, M.S., Aicardi, I., Alicandro, M., Allasia, P., Baldo, M., De Berardinis, P., Dominici, D., Godone, D., Hobbs, P., Lechner, V., Niedzielski, T., Piras, M., Rotilio, M., Salvini, R., Segor, V., Sotier, B., Troilo, F.: The use of Unmanned Aerial Vehicles (uavs) for engineering geology applications. Bulletin of Engineering Geology and the Environment. 79, 3437–3481 (2020).
5. Otto, A., Agatz, N., Campbell, J., Golden, B., Pesch, E.: Optimization approaches for civil applications of Unmanned Aerial Vehicles (uavs) or aerial drones: A survey. Networks. 72, 411–458 (2018).
6. Chittoor, P.K., Chokkalingam, B., Mihet-Popa, L.: A review on UAV Wireless Charging: Fundamentals, applications, charging techniques and standards. IEEE Access. 9, 69235–69266 (2021).
7. Tsouros, D.C., Bibi, S., Sarigiannidis, P.G.: A review on UAV-based applications for Precision Agriculture. Information. 10, 349 (2019).
8. Mohan, M., Richardson, G., Gopan, G., Aghai, M.M., Bajaj, S., Galgamuwa, G.A., Vastaranta, M., Arachchige, P.S., Amorós, L., Corte, A.P., de-Miguel, S., Leite, R.V., Kganyago, M., Broadbent, E.N., Doaemo, W., Shorab, M.A., Cardil, A.: UAV-supported Forest Regeneration: Current trends, challenges and implications. Remote Sensing. 13, 2596 (2021).
9. Martinez, J.L., Lucas-Borja, M.E., Plaza-Alvarez, P.A., Denisi, P., Moreno, M.A., Hernández, D., González-Romero, J., Zema, D.A.: Comparison of satellite and drone-based images at two spatial scales to evaluate vegetation regeneration after post-fire treatments in a mediterranean forest. Applied Sciences. 11, 5423 (2021).
10. Mukhamediev, R.I., Symagulov, A., Kuchin, Y., Zaitseva, E., Bekbotayeva, A., Yakunin, K., Assanov, I., Levashenko, V., Popova, Y., Akzhalova, A., Bastaubayeva, S., Tabynbaeva, L.: Review of some applications of unmanned aerial vehicles technology in the resource-rich country. Applied Sciences. 11, 10171 (2021).
11. Global market for commercial applications of drone technology valued at over $127BN, https://pwc.blogs.com/press_room/2016/05/global-market-for-commercial-applications-of-drone-technology-valued-at-over-127bn.html, accessed 2021/09/16.
12. Mukhamediev, R., Kuchin, Y., Yakunin, K., Symagulov, A., Ospanova, M., Assanov, I., Yelis, M.: Intelligent unmanned aerial vehicle technology in Urban Environments. Communications in Computer and Information Science. 345–359 (2020).

13. (https://www.gov.kz/), Министерства РК: 277 unmanned aerial vehicles are registered in Kazakhstan, https://online.zakon.kz/Document/?doc_id=37316914&pos=3%3B-82#pos=3;-82, accessed 2022/06/20.
14. Drone mapping software, https://www.opendronemap.org/, accessed 2022/06/20.
15. Han, Y.-G., Yoo, S.H., Kwon, O.: Possibility of applying unmanned aerial vehicle (UAV) and mapping software for the monitoring of waterbirds and their habitats. Journal of Ecology and Environment. 41, (2017).
16. Chen, Q., Wen, X., Wu, F., Yang, Y.: Defect detection and health monitoring of steel structure based on UAV integrated with Image Processing System. Journal of Physics: Conference Series. 1176, 052074 (2019).
17. Montoya, J.C., Muñoz, C.Q., Márquez, F.P.: Remote Condition Monitoring for photovoltaic systems. Non-Destructive Testing and Condition Monitoring Techniques for Renewable Energy Industrial Assets. 133–142 (2020).
18. UAVs for monitoring pipelines and oil and gas facilities, https://brlab.ru/scopes/monitoring/ accessed 2021/09/16 .
19. Ribeiro, R.G., Junior, J.R., Cota, L.P., Euzebio, T.A., Guimaraes, F.G.: Unmanned aerial vehicle location routing problem with charging stations for belt conveyor inspection system in the mining industry. IEEE Transactions on Intelligent Transportation Systems. 21, 4186–4195 (2020).
20. Aasen, H., Honkavaara, E., Lucieer, A., Zarco-Tejada, P.: Quantitative Remote Sensing at ultra-high resolution with UAV spectroscopy: A review of sensor technology, measurement procedures, and data correction workflows. Remote Sensing. 10, 1091 (2018).
21. Jakob, S., Zimmermann, R., Gloaguen, R.: The need for accurate geometric and radiometric corrections of drone-borne hyperspectral data for Mineral Exploration: MEPHySTo—a toolbox for pre-processing drone-borne hyperspectral data. Remote Sensing. 9, 88 (2017).
22. Luo, C., Miao, W., Ullah, H., McClean, S., Parr, G., Min, G.: Unmanned aerial vehicles for Disaster Management. Springer Natural Hazards. 83–107 (2018).
23. Martínez-Vargas, A., Rodríguez-Cortés, G.L., Montiel-Ross, O.: Comparative representations of a genetic algorithm to locate unmanned aerial vehicles in disaster zones, http://www.engineeringletters.com/issues_v27/issue_2/EL_27_2_14.pdf, (2019).
24. Kamilaris, A., X. Prenafeta-Boldú, F.: Disaster Monitoring using Unmanned Aerial Vehicles and Deep Learning. Disaster Management for Resilience and Public Safety Workshop.
25. Ho, F., Salta, A., Geraldes, R., Goncalves, A., Cavazza, M., Prendinger, H. In: 18th International Conference on Autonomous Agents and multiagent systems (Aamas 2019): Montreal, Canada 13-17 May 2019.
26. Medvedev, A.A.; Alekseyenko, N.y.A.y.; Karpenko, I.O: Monitoring of wildlife in specially protected natural areas using unmanned aerial vehicles. Bulletin of the Samara Scientific Center of the Russian Academy of Sciences, (2015).
27. Mohd Noor, N., Abdullah, A., Hashim, M.: Remote Sensing UAV/drones and its applications for urban areas: A Review. IOP Conference Series: Earth and Environmental Science. 169, 012003 (2018).
28. Report, S.: Drone inspections help cut pollution by half, https://gulfnews.com/uae/environment/drone-inspections-help-cut-pollution-by-half-1.2263928, accessed 2021/09/16.
29. Tatum, M.C., Liu, J.: Unmanned Aircraft System applications in construction. Procedia Engineering. 196, 167–175 (2017).
30. Bondi, E., Fang, F., Hamilton, M., Kar, D., Dmello, D., Choi, J., Hannaford, R., Iyer, A., Joppa, L., Tambe, M., Nevatia, R.: Automatic detection of poachers and wildlife with uavs. Artificial Intelligence and Conservation. 77–100 (2019).

31. UAV radiation mapping drone and AARM system, https://www.kromek.com/product/aerial-radiation-mapping-drone, accessed 2021/09/16.
32. Automation, Industrial: Air pollution can now be detected using UAVs with gas sensors, https://vk.com/@industriation-uroven-zagryazneniya-vozduha-teper-mozhno-opredelit-s-pomosc.
33. Corcoran, E., Winsen, M., Sudholz, A., Hamilton, G.: Automated detection of wildlife using drones: Synthesis, opportunities and constraints. Methods in Ecology and Evolution. 12, 1103–1114 (2021).
34. Liang, X., Zhao, S., Chen, G., Meng, G., Wang, Y.: Design and development of ground station for UAV/UGV Heterogeneous Collaborative System. Ain Shams Engineering Journal. 12, 3879–3889 (2021).
35. Alhaqbani, A., Kurdi, H., Youcef-Toumi, K.: Fish-inspired task allocation algorithm for multiple unmanned aerial vehicles in search and rescue missions. Remote Sensing. 13, 27 (2020).
36. Alotaibi, E.T., Alqefari, S.S., Koubaa, A.: LSAR: Multi-uav collaboration for search and Rescue Missions. IEEE Access. 7, 55817–55832 (2019).
37. King, E.: Aerial drones in mineral exploration, https://www.geologyforinvestors.com/aerial-drones-in-mineral-exploration, accessed 2021/09/16.
38. Jackisch, R., Zimmermann, R., Lorenz, S., Saartenoja, A., Pirttijärvi, M., Gloaguen, R.: Integration of drone-borne hyperspectral and geomagnetic data. A combined approach in geologic remote sensing. 20th EGU General Assembly. (2018).
39. Murray, C.C., Raj, R.: The multiple flying sidekicks traveling salesman problem: Parcel Delivery with multiple drones. Transportation Research Part C: Emerging Technologies. 110, 368–398 (2020).
40. Villa, D.K., Brandão, A.S., Sarcinelli-Filho, M.: A survey on Load Transportation using multirotor uavs. Journal of Intelligent & Robotic Systems. 98, 267–296 (2019).
41. Bacco, M., Berton, A., Gotta, A., Caviglione, L.: IEEE 802.15.4 Air-ground UAV Communications in smart farming scenarios. IEEE Communications Letters. 22, 1910–1913 (2018).
42. Bouhamed, O., Ghazzai, H., Besbes, H., Massoud, Y.: A UAV-assisted data collection for wireless sensor networks: Autonomous Navigation and Scheduling. IEEE Access. 8, 110446–110460 (2020).
43. Busnel, Y., Caillouet, C., Coudert, D.: Self-organized disaster management system by distributed deployment of connected uavs. 2019 International Conference on Information and Communication Technologies for Disaster Management (ICT-DM). (2019).
44. Hasan, N.U., Valsalan, P., Farooq, U., Baig, I.: On the recovery of terrestrial wireless network using cognitive uavs in the disaster area. International Journal of Advanced Computer Science and Applications. 11, (2020).
45. Aljehani, M., Inoue, M.: Performance evaluation of multi-UAV system in Post-Disaster Application: Validated by Hitl Simulator. IEEE Access. 7, 64386–64400 (2019).
46. Vazquez-Carmona, E.V., Vasquez-Gomez, J.I., Herrera-Lozada, J.C., Antonio-Cruz, M.: Coverage path planning for spraying drones. Computers & Industrial Engineering. 168, 108125 (2022).
47. Araujo, J.F., Sujit, P.B., Sousa, J.B.: Multiple UAV area decomposition and coverage. 2013 IEEE Symposium on Computational Intelligence for Security and Defense Applications (CISDA). (2013).
48. Hong, Y., Jung, S., Kim, S., Cha, J.: Autonomous Mission of Multi-UAV for Optimal Area Coverage. Sensors. 21, 2482 (2021).
49. Petritoli, E., Leccese, F., Ciani, L.: Reliability and maintenance analysis of Unmanned Aerial Vehicles. Sensors. 18, 3171 (2018).

50. Fesenko, H., Kharchenko, V., Bardis, N., Kor, A.-L., Brezhniev, Y.: Drone fleet survivability evaluation based on Lanchester's modified deterministic model. International Journal of Circuits, Systems and Signal Processing. 14, 775–781 (2020).
51. Natvig, B.: Multistate System Reliability. Wiley Encyclopedia of Operations Research and Management Science. (2011).
52. Kliushnikov, I., Kharchenko, V., Fesenko, H. An Unmanned Aerial Vehicle as a Multi-State System, Proceedings - 16th International Conference on Advanced Trends in Radioelectronics, Telecommunications and Computer Engineering, TCSET 2022, (2022), pp. 291–296.
53. Dui, H., Zhang, C., Bai, G., Chen, L.: Mission Reliability Modeling of UAV SWARM and its structure optimization based on importance measure. Reliability Engineering & System Safety. 215, 107879 (2021).
54. Rusnak, P., Kvassay, M., Zaitseva, E., Kharchenko, V., Fesenko, H.: Reliability assessment of heterogeneous drone fleet with sliding redundancy. 2019 10th International Conference on Dependable Systems, Services and Technologies (DESSERT). (2019).
55. Amari, S.V., Dill, G.: A new method for reliability analysis of Standby Systems. 2009 Annual Reliability and Maintainability Symposium. (2009).
56. Tannous, O., Xing, L., Rui, P., Xie, M., Ng, S.H.: Redundancy allocation for series-parallel warm-standby systems. 2011 IEEE International Conference on Industrial Engineering and Engineering Management. (2011).
57. Kumar, A., Yadav, A.S., Gill, S.S., Pervaiz, H., Ni, Q., Buyya, R.: A secure drone-to-drone communication and software defined drone network-enabled Traffic Monitoring System. Simulation Modelling Practice and Theory. 120, 102621 (2022).
58. Yu, Y., Shi, C., Shan, D., Lippiello, V., Yang, Y.: A hierarchical control scheme for multiple aerial vehicle transportation systems with uncertainties and state/input constraints. Applied Mathematical Modelling. 109, 651–678 (2022).
59. Behera, T.K., Bakshi, S., Sa, P.K.: Vegetation extraction from UAV-based aerial images through deep learning. Computers and Electronics in Agriculture. 198, 107094 (2022).
60. Maurya, H.L., Singh, P., Behera, L., Verma, N.K.: Control design for unmanned aerial vehicle using fractional order backstepping control and extended homogenous control. 2021 International Symposium of Asian Control Association on Intelligent Robotics and Industrial Automation (IRIA). (2021).
61. Levitin, G., Xing, L., Dai, Y.: Heterogeneous 1-out-of-N standby systems with limited unit Operation Time. Reliability Engineering & System Safety. 224, 108532 (2022).
62. Schneeweiss, W.G.: A short boolean derivation of mean failure frequency for any (also noncoherent) system. Reliability Engineering & System Safety. 94, 1363–1367 (2009).
63. Zaitseva, E., Levashenko, V., Kostolny, J.: Importance analysis based on logical differential calculus and binary decision diagram. Reliability Engineering & System Safety. 138, 135–144 (2015).
64. Akers: Binary decision diagrams. IEEE Transactions on Computers. C-27, 509–516 (1978).
65. P. A. Coolen, F., Coolen-Maturi, T.: Generalizing the Signature to Systems with Multiple Types of Components. Advances in Intelligent and Soft Computing. 170, 115–130 (2012).
66. Heidtmann, K.D.: Improved method of inclusion-exclusion applied to K-out-of-N systems. IEEE Transactions on Reliability. R-31, 36–40 (1982).
67. Rausand, M., Hoyland, A.: System Reliability Theory: Models, Statistical Methods, and Applications, https://www.scirp.org/(S(lz5mqp453edsnp55rrgjct55))/reference/ReferencesPapers.aspx?ReferenceID=1821349.
68. Vachtsevanos, G., Ludington, B. Unmanned aerial vehicles: Challenges and technologies for improved autonomy, WSEAS Transactions on Systems, 5(9), (2006), pp. 2164-2171

69. Kuo, W., X., Zhu. Importance Measures in Reliability, Risk, and Optimization: Principles and Applications. (2012). Chichester, UK: Wiley.
70. Talantsev, A.D. Analysis and Synthesis of Certain Electric Circuits by Means of Special Logical Operators, Automation and Remote Control 20, 874-883. (1959).
71. Steinbach, B., C. Posthoff. Boolean Differential Equations, Morgan & Claypool Publishers. (2013)
72. Kvassay, M., Zaitseva,E., Levashenko, V., Kostolny, J. Binary Decision Diagrams in reliability analysis of standard system structures, Proceedings of *2016 International Conference on Information and Digital Technologies (IDT)*, 164-172.
73. Kvassay, M., Zaitseva, E.: Topological analysis of multi-state systems based on direct partial logic derivatives. Springer Series in Reliability Engineering. 265–281 (2017).