IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 4 January 2024, accepted 14 January 2024, date of publication 24 January 2024, date of current version 1 February 2024.

Digital Object Identifier 10.1109/ACCESS.2024.3358198

RESEARCH ARTICLE

Availability of UAV Fleet Evaluation Based on Multi-State System

ELENA ZAITSEVA[1], (Member, IEEE), VITALY LEVASHENKO[1], (Member, IEEE), VLADIMIR MYSKO[2], STANISLAW CZAPP[3], (Member, IEEE), AND DARKHAN ZHAXYBAYEV[2]

[1]Department of Informatics, University of Žilina, 010 26 Žilina, Slovakia
[2]Higher School of Information Technology, West Kazakhstan Agrarian-Technical University named after Zhangir Khan, 090009 Uralsk, Kazakhstan
[3]Department of Electrical Power Engineering, Gdańsk University of Technology, 80-233 Gdańsk, Poland

Corresponding author: Elena Zaitseva (elena.zaitseva@fri.uniza.sk)

This work was supported in part by the Polish National Agency for Academic Exchange; in part by the Slovak Research and Development Agency with the Project "Application of Multi-State System Reliability Analysis for Electrical Low-Voltage Systems" under Grant SK-PL-21-0003; and in part by the Ministry of Education, Science, Research, and Sport of the Slovak Republic with the Project "New Approaches of Reliability Analysis of Non-Coherent Systems" under Grant VEGA 1/0165/21.

ABSTRACT Unmanned Aerial Vehicle (UAV) applications are extended extremely. Some applications need to use several UAVs for a general mission which can be considered a UAV fleet. One of the important characteristics for the evaluation of a UAV or UAV fleet is reliability. There are studies in which methods for analysis of their reliability are considered. Reliability analysis of UAV fleets is less frequently studied, although a single UAV cannot be performed in many applications and requires the involvement of multiple UAVs. Typically, this analysis is based on evaluating two states as operational/functioning and faulting. This paper proposes a new method to calculate the availability of a UAV fleet as one of the reliability characteristics. Unlike well-known UAV fleet analysis approaches, in this paper, the availability is studied based on a mathematical model of a Multi-State System (MSS). MSS allows us to examine more than two states (operational and faulty) of the system, so this analysis is more detailed. In this paper, based on MSS, the analysis of various topologies of UAV fleets is implemented. This mathematical model is used for the analysis and evaluation of topologies of homogeneous and heterogeneous UAV fleets, which can be irredundant or redundant hot stable systems. The interpretations of different topologies of fleets as typical structures of MSS (series, parallel, k-out-of-n) are considered. New mathematical definitions of the availability of UAV fleets of different topologies based on MSS structure function are proposed. These definitions allowed us to consider the influence of the number of UAVs on the UAV fleet availability and compare the availabilities of considered topologies of fleets.

INDEX TERMS Availability, fleet, k-out-of-n system, multi-state system, series system, structure function, UAV.

I. INTRODUCTION

The use of UAVs is one of the main trends in industrial technology at present. As was shown in the reviews [1] and [2], the use of UAVs is successfully implemented in a variety of industries, such as agriculture, geological exploitation, and mining, monitoring hazardous geophysical processes, environmental pollution monitoring, monitoring of technical and engineering structures, traffic monitoring and others. Some UAV-based applications, for example, such as monitoring, are implemented by group UAVs. The group of UAVs developed for implementing a general mission is considered a UAV fleet or swarm [3], [4]. One of the important conditions for the successful applications of UAVs or UAV fleets is their reliability [5]. Reliability is a complex characteristic of the system which includes several metrics, indices, and measures [6], [7]. There are many studies on the reliability analysis and evaluation of a single UAV [8]. The analysis of UAV fleet reliability at the presented time is not investigated well and according to [5] these investigations have 4% in domine of

The associate editor coordinating the review of this manuscript and approving it for publication was Haidong Shao.

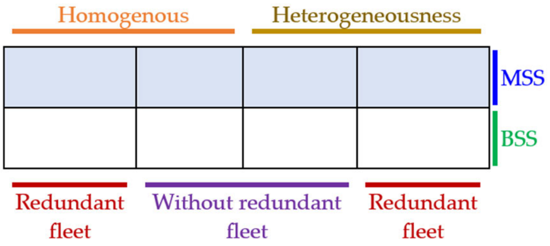


FIGURE 1. UAV fleets reliability analysis classification.

reliability analysis of UAV. Therefore, in this paper, we would like to develop new mathematical models for the evaluation of UAV fleets taking into account some factors such as topology, heterogeneity, and redundancy.

In the study [9] authors introduce the background for the systematization of UAV fleet characteristics for the evaluation of its reliability. One of these characteristics is the mathematical model, which is used for a fleet reliability analysis: *Binary State System* (BSS) and *Multi-State System* (MSS). BSS is a mathematical model that allows the definition and analysis of two states for the system and its components only. These states are a failure and functioning [10], [11]. MSS is the more general mathematical model, which supposes the analysis and evaluation of several performance levels (more than two) for a system and its components [12]. MSS allows the provision of reliability analysis in more detail but needs higher computational resources. For example, MSS allows us to investigate the degradation in the reliability of the system. Most of the investigations in UAV fleet reliability analysis are based on the use of BSS. For example, BSS as mathematical model is used in studies [6], [13] – [16]. The use of MSS for reliability analysis of UAV fleets allows us to consider fleet behavior in more detail. MSS has been used in the reliability analysis of UAV in [17], [18]. The authors in [17] propose a general classification of multi-state UAV-based monitoring systems depending on redundant UAVs of the fleet, automatic battery maintenance stations, and other parameters. The problem of the UAV fleet balancing based on the MSS Markov model is considered in [18]. However, the mathematical models of different UAV fleets and their comparison were not considered in these studies. According to the study [5], the UAV fleets taking into consideration the mathematical model for reliability analysis can be classified in the form of the Karnaugh map (Fig. 1). Mathematical models of UAV fleets based on BSS were proposed in [5]. In this paper, we propose considering UAV fleet reliability analysis based on the MSS as a mathematical model, particularly the availability of different UAV fleet types. New definitions and expressions of availability are proposed for UAV fleets that are homogenous or heterogenous, irredundant or redundant, and also have different types of control.

There are several representations of MSS in reliability analysis that cause the mathematical methods used for the calculation of indices, metrics, and measures of system reliability [12]. One of them is structure function, which maps all possible component states to the system state. The MSS structure function of the UAV fleet is used in this study to develop new expressions for the calculation of the availability of the fleet depending on its characteristics such as heterogeneity and redundancy (Fig.1). The evaluation of different fleets of UAVs based on the structure function of BSS has been in paper [5]. The investigation of UAV fleets based on BSS doesn't allow analysis and evaluation of states other than operational and failure. For example, the UAV fleet degradation cannot be quantified based on BSS without the development of a special method, but it is possible based on MSS. In this paper, the structure functions are defined for different fleets based on MSS, and these definitions are used for the development of expressions for available calculation. In addition to the mathematical model, when analyzing the reliability of a UAV fleet, topological properties such as heterogeneity and redundancy are taken into account (Fig.2). The availability of a UAV fleet is defined depending on heterogeneity, redundancy, and type of control and can be calculated for:

- Heterogenous redundant UAV fleet with central control (HeRC)
- Heterogenous redundant UAV fleet with decentral control (HeRD)
- Heterogenous irredundant UAV fleet with central control (HeIC)
- Heterogenous irredundant UAV fleet with decentral control (HeID)
- Homogenous redundant UAV fleet with central control (HoRC)
- Homogenous redundant UAV fleet with decentral control (HoRD)
- Homogenous irredundant UAV fleet with central control (HoIC)
- Homogenous irredundant UAV fleet with decentral control (HoID)

The paper is organized as follows: the state of the art of the paper's subject is considered in section II. The mathematical background for MSS reliability analysis is introduced in section III. In this section, the typical structures of UAV fleets studied based on BSS are generalized for the MSS mathematical model. The principal conceptions of MSS reliability analysis for UAV fleets of different structures taking into consideration the homogenous, heterogeneous, and redundancy of a fleet are considered in section III-A. New definitions of the availability of different topologies of UAV fleets based on MSS and expressions for the calculation are introduced in section III-B. The application of the proposed algorithms for the calculations of availability for the different types of UAV fleets is shown in section IV. The case studies of irredundant and redundant fleets with homogenous and heterogeneous structures are considered in section IV-A. The analysis of the fleet's parameters (number of UAVs, number of functioning

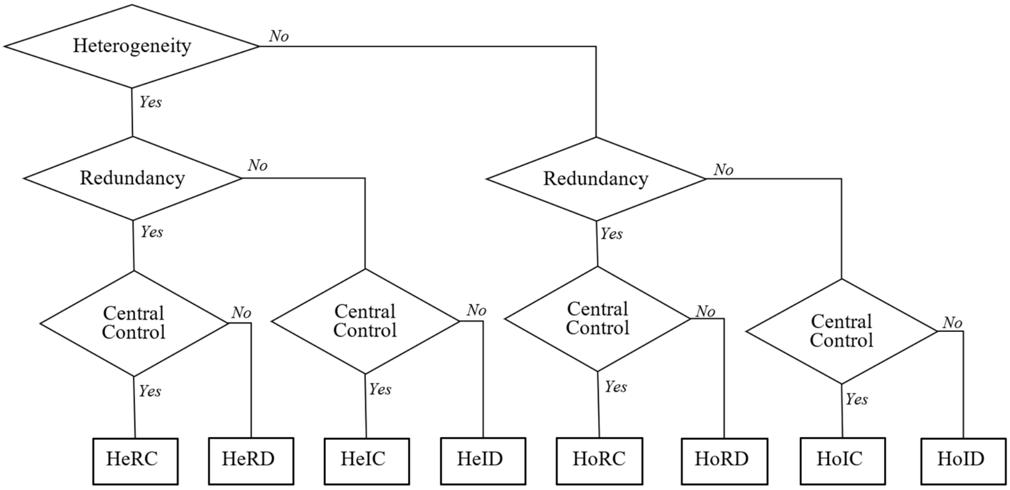


FIGURE 2. **Availability of UAV fleet definitions and calculations depending on the topology aspects.**

UAVs in redundant fleet) is discussed in section IV-B. Advantages, limitations of the proposed algorithms, and future researchers are in section V.

II. THE PROBLEM STATE ANALYSIS: METHODS FOR RELIABILITY EVALUATION OF UAV FLEETS

Reliability is one of the main characteristics of any system, including UAVs and UAV fleets. There are many studies on the reliability analysis of UAVs [5], [14], [19]. The reliability aspects of UAV missions and UAV fleet missions are considered in some papers too. In particular, authors investigate UAV missions taking into consideration the problem of redundancy [20], maintenance [19], prognostic and health management [21], and safety [22]. Some aspects of UAV missions are evaluated based on methods of machine learning and artificial intelligence [15], [23] – [25]. Studies [13], [19] – [22], [26] take into account the possibility of mission implementation by the UAV fleet, but the fleet is not the subject of investigations and mission success is evaluated as the first, and the fleet's reliability and its factors are not examined. The reliability of a UAV fleet is influenced by many factors such as its structure or topology [16], [27], type of redundancy [13], [28], drone characteristics [29], heterogeneity [30], and others. The taxonomy in reliability analysis of UAV fleets has been proposed in [9] that shows the important factors of this analysis and one of them is the development of the mathematical model of UAV fleet.

The mathematical model of the UAV fleet, as the first, should be defined depending on the number of performance levels of the fleet. In this step, the mathematical model can be defined as BSS, for the evaluation of two performance levels, or MSS, for the analysis of more than two performance levels. Most studies of UAV fleet reliability and its special aspects are based on BSS [3], [4], [6], [13] – [16], [28], [30]. The topological aspects of UAV fleets closely correlate with reliability and are taken into account in fleet reliability.

The reliability of the UAV fleet depends on the heterogeneity of this system. Two types of systems can be defined depending on this aspect: homogenous UAV fleet [30] and heterogeneous UAV fleet [31]. The type of fleet depending on this aspect is caused by the characteristics and properties of UAVs in a fleet. The fleet is homogenous if all UAVs are identical [26], [30], [32]. But most often, the heterogeneous fleets are used in real-world applications [31], [33]. The homogenous UAV fleet based on MSS is considered in [26]. But in this study, the specifics of the system degradation from the point of view of the mission are considered and the calculation of any UAV fleet metrics or indices are not studied. The aspect of heterogeneity in papers [30] – [33] is investigated based on BSS.

One of the often-considered reliability analysis aspects of UAV fleets is redundancy. The redundancy is supposed that some UAVs in the fleet are reserved and the failures of some UAVs in the fleet don't result in the mission fault. An irredundant UAV fleet is used if the resources are restricted. The reliability of an irredundant UAV fleet is considered in the context of UAV path planning often and investigated by BSS [14], [15]. The comparison of irredundant and redundant fleets based on BSS is implemented in [13]. Typically, the redundancy of the UAV fleet is interpreted as a k-out-of$-n$ system, which means that the fleet is functioning state (state of mission implementation) if minimal k UAVs are working [27]. BSS $k-$out-of$-n$ system, for example, is used in [16] as the mathematical model for the definition of the fleet structure (triangular and quadrilateral UAV fleets) depending on conditional reliability, conditional failure rate, and remaining useful life. Influences of system parameters k and n on fleet reliability are shown by empirical studies in [6]. The research of UAV fleet redundancy [13], [14] – [16], [27] allows the analysis of two fleet states (operational and fault), but a more detailed investigation is not possible based on BSS, for example, fleet degradation. Such investigation can be implemented based on MSS.

One more aspect of UAV fleet topology that influenced its reliability is the control type of fleet. In the investigations [34], [35] the control of the UAV fleet is discussed such as decentral or central. In the case of central control, the central control unit is used for fleet control, it can be a moving ground platform on which UAVs are recharged and refueled [34]. The influence of control type on UAV fleet reliability is mentioned in the taxonomy of reliability analysis in UAVs and UAV fleets [9].

The analysis of the studies in reliability analysis of UAV fleet shows that the problem of MSS used for reliability evaluation of fleet is not developed sufficiently. However, it is the MSS allows a detailed assessment of a system's reliability, taking into consideration not only the fault and operational states of a system but also its degradation.

III. RELIABILITY ANALYSIS OF UAV FLEET METHOD

In this section, the calculation of UAV fleet availability based on MSS is proposed. New algorithms for the calculation of the availability for different topologies of the fleet are developed. The evaluation of the UAV fleet and other objects in reliability analysis can be implemented based on different mathematical approaches. The most often used mathematical approaches in reliability analysis are the Markov model [17], Monte-Carlo Simulation [36], Bayesian Network [37], and algebra logic (structure function) [5], [12]. Each of these mathematical methods allows the evaluation of specific properties of reliability. For example, the Markov model and Bayesian network are employed for the analysis of the system reliability depending on time. The methods based on algebra logic, including fault tree and Reliability Block Diagram (RBD), are typically used for the structural or topological reliability evaluation of the system. This study develops the structure function based methods for availability analysis of UAV fleets. The background of UAV fleet availability analysis is briefly discussed in section III-A below. New definitions and expressions for availability calculation are introduced in section III-B.

A. MSS STRUCTURE FUNCTION BACKGROUND FOR A UAV FLEET

The structure function of a system can be defined for two types of mathematical models: BSS and MSS. BSS is a special case of MSS. The mathematical model of a UAV fleet defined by MSS structure function is [5]:

$$\phi(x_1,\ldots,x_n)=\phi(\boldsymbol{x}):\{0,\ldots,m_1-1\}\times\ldots\times\{0,\ldots,m_n-1\}\rightarrow\{0,\ldots,M-1\} \quad (1)$$

where n is the number of UAVs in the fleet; x_i is the variable representing the state of the ith component (UAV) and $\boldsymbol{x} = (x_1, \ldots, x_n)$ is the state vector that accumulates states of all system components (UAVs of the fleet); m_i for $i = 1, \ldots, n$ defines the number of states of the ith UAV: zero agrees with its fault and $m_i - 1$ is perfect functioning; the system performance levels of the fleet are defined from zero to $M-1$ that are interpreted as a failure of the fleet and perfect functioning accordingly.

The structure function of MSS (1) can be used for the development of the mathematical model of a UAV fleet. Need to note, the MSS structure function (1) is BSS structure function if $m_i = M = 2$ $(i = 1, \ldots, n)$: $\phi(\boldsymbol{x})$: $\{0, 1\}^n\rightarrow\{0, 1\}$.

The structure function (1) depends on the heterogeneous [30] and homogenous [31] structures of the fleet. The homogenous structure is formed by the same UAVs, which have equal probabilities of functioning. It simplifies the calculation of the fleet availability and reliability. In addition, the MSS structure function of a homogenous fleet is defined as:

$$\phi(x_1,\ldots,x_n)=\phi(x):\{0,\ldots,m-1^n\}\rightarrow\{0,\ldots,m-1\} \quad (2)$$

One more important property of the UAV fleet is redundancy. The irredundant fleet is interpreted from the point of view of reliability analysis as a series system of n components:

$$\phi\,(\boldsymbol{x}) = \bigwedge\nolimits_{i=1}^{n} x_i \quad (3)$$

where the symbol ∧ Boolean operator AND

This topology is used to minimize the overall energy consumption and the number of UAVs used to ensure non-redundant exploitation of resources [32], [38]. The redundancy (Fig.1) should be considered at the level of fleet and level of UAV [28]. Typically, in reliability analysis, two types of redundancy are investigated. Active redundancy supposes the introduction of a system structure of additional components that are involved in the system's functioning. in the case of a UAV fleet, it is redundant drones in the structure of the fleet. The standby redundancy is based on the involvement of additional components as components involved in the operation of the system fail. This redundancy can be hot, cold, and warm [38]. Hot standby sparing is used as a failover mechanism wherein the recovery time is critical. The mathematical model for this type of redundancy is equal to active redundancy if the switching delays are not considered. In the case of cold standby sparing, the spare component starts functioning only when the working component fails and needs to be replaced. This type of sparing is typically used in systems that are critical for energy consumption. The time delays when a new component is put into operation are important for cold standby. In some cases, reliability analysis considers such systems as phase mission systems [27]. The analysis and evaluation of such a system are typically implemented based on methods that study the reliability of a system depending on time, for example, the Markov model or Monte Carlo simulation. The warm standby can be considered as the combination of two previous and is not included in the consideration in this study. Therefore, in this paper, the hot stable redundancy is used for the definition of the topology of the redundant UAV fleet. The redundant UAV fleet is typically a k−out-of−n system in reliability analysis [6], [16]. The structure function of this system is defined as the unit of the minimal paths. Each minimal path of the k−out-of−n MSS system includes k variables of the structure function and can be presented as $\bigwedge_{w=1}^{k} x_{i_w}$ (where the symbol $\wedge$ Boolean operator AND and for the minimal path it is conjunction k variables):

$$\phi(\boldsymbol{x}) = \bigvee_{Q_k} \bigwedge_{w=1}^{k} x_{i_w} \tag{4}$$

where $\vee$ is the symbol of Boolean operation OR for Q_k minimal paths in the topology of the k-out-of−n system and the number of the paths Q_k is defined as:

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

In addition to the fleet type (homogeneous and heterogeneous) and the redundancy, the control of a fleet is taken into consideration in this study. According to studies [34], [35], [39], it can be decentralized and centralized. In the case of centralized control, according to [34] and [40], all UAVs are ''connected'' with the control component. From a topological point of view in reliability analysis, such a connection is serial.

The UAV fleet structure or topology in reliability analysis can be evaluated based on the availability. MSS availability is defined for each working performance level of a system based on the MSS structure function (1) according to [19]:

$$A^{(j)} = \Pr\{\phi(x) \geq j\},\ j = 1, \ldots, M-1 \tag{6}$$

or for BSS [11]:

$$A = \Pr\{\phi(x) = 1\}, \tag{7}$$

Note, that the availability of MSS (6) is defined for each functioning performance level of a fleet. The definitions of availability (6) and (7) allow us to evaluate and compare the availability of typical topologies of UAV fleets. The availability of the UAV fleet (6) or (7) depends on the probabilities of the UAV states. In this paper, the probabilities of the i−th UAV fault and functioning for BSS are denominated as q_i and p_i and the i−th UAV state s ($s = 0, \ldots, m_i - 1$) for MSS is defined as $p_{i,s}$.

The unavailability of MSS is defined for each functioning performance level of a system as [12]:

$$U^{(j)} = \Pr\{\phi(x) < j\} = 1 - A^{(j)},\ j = 1, \ldots, M-1. \tag{8}$$

The unavailability of BSS is computed as:

$$U = \Pr\{\phi(x) = 0\} = 1 - A. \tag{9}$$

B. AVAILABILITY OF TYPICAL TOPOLOGIES OF UAV FLEETS

In this paper, the homogenous and heterogeneous topologies of the UAV fleet are considered. For each of them, the availability is computed based on the mathematical model of MSS. The hot redundancy is taken in the analysis of the UAV fleet availability computation too. Irredundant flotilla topologies are also examined since they are often used in practical problems where the number of UAVs is limited [32], [39]. The considered topologies are examined for central and decentral control of a fleet.

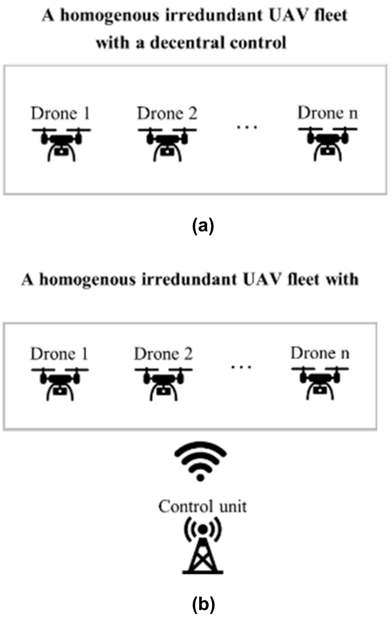


FIGURE 3. Homogenous irredundant UAV fleet with decentral (a) and central (b) control.

The homogenous structure of the UAV fleet supposes that all UAVs have equal characteristics and probabilities of performance levels. The structure function of this fleet is defined by (2). The probabilities of equal states of different UAVs in this fleet are equal: $p_{i,s} = p_{v,s} = \tilde{p}_s$ for $i \neq v$ (i, v = 0, …, n). This type of fleet is used in case of The irredundant structure of a homogenous fleet (Fig.3) is interpreted as a series system because the fleet performs its mission if all the UAVs are in functional states. The irredundant homogenous structure should be considered in two versions: with decentral control [31] and central control [34]. In the case of the central control, n UAVs have a connection with a central control unit (Fig.3 (b)). In reviews of control systems of UAV fleets [34], [35], the control unit is a serial component of the system. Therefore, a fleet with decentral control is interpreted as a system of n components and a fleet with a control unit is considered as a system of $(n+1)$ components, in which the $(n+1)$−th serial component is a control unit. The homogenous irredundant topology with central control is typical for fleets in which one of the UAVs performs control functions [34] and therefore has similar technical characteristics to other UAVs of the fleet.

The availability of the irredundant homogenous UAV fleet without central control (it is decentral) according to (6) is:

$$A_{HoID}^{(j)} = \Pr\left\{\bigwedge_{x=1}^{n} x_i \geq j\right\} = \left(\sum_{s=j}^{m-1} \tilde{p}_s\right)^n \tag{10}$$

```
// The calculation of $A^{(j)}_{HoID}$
Initial data:
   $n$ - number of UAVs;
   $m$ - number of states of UAVs and fleet;
   $j$ - performance level $j$ of the UAV fleet;
   $p_0$, …, $p_s$, …, $p_{m-1}$ - the probabilities of UAV
      states 0, .., $s$,.., $m$-1;

// Calculation of availability
   sum = 0; $s$ = $j$;
   do { sum = sum + $p_s$ ; $s$++;}
   while ($s$ < $m$);
   $A^{(j)}_{HoID}$= sum ^ $n$;
```

(a)

```
// The calculation of $A^{(j)}_{HoIC}$
Initial data:
   $n$ - number of UAVs;
   $m$ - number of states of UAVs and fleet;
   $j$ - performance level $j$ of the UAV fleet
   $p_0$, …, $p_s$, …, $p_{m-1}$ - the probabilities of
      UAV/control unit states 0, .., $s$,.., $m$-1;

// Calculation of availability
   sum = 0; $s$ = $j$;
   do { sum = sum + $p_s$ ; $s$++;}
   while ($s$ < $m$);
   $A^{(j)}_{HoID}$= sum ^ ($n$+1);
```

(b)

FIGURE 4. **The calculation of availability of a homogenous irredundant UAV fleet with decentral (a) and central (b) control.**

and for the UAV fleet with central control:

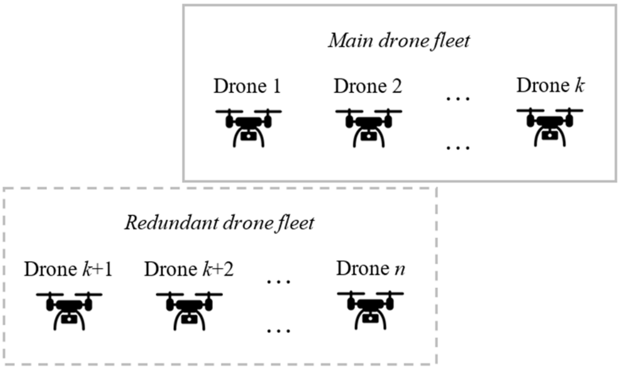
$$A^{(j)}_{HoIC} = \Pr\left\{\left(\bigwedge\nolimits_{x=1}^{n} x_i\right) x_{n+1} \geq j\right\} = \left(\sum\nolimits_{s=j}^{m-1} \tilde{p_s}\right)^{n+1} \tag{11}$$

where x_i $(i = 1, \ldots, n)$ is UAV i of fleet and x_{n+1} is central control unit; $\tilde{p_s}$ is the probability of state s of the UAV (for components from 1 to n) or central control unit as $(n + 1)$ component $(s = 0, \ldots, m - 1)$; $j = 1, \ldots, m - 1$.

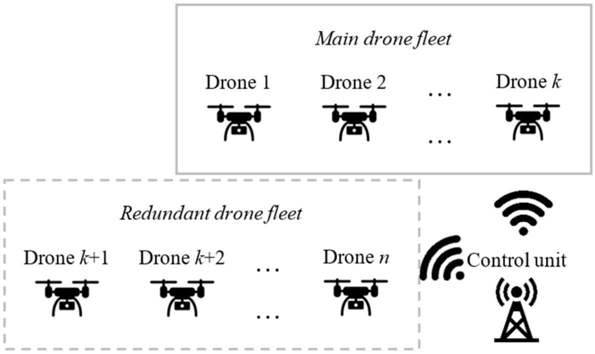
The pseudocodes for the calculation of the availabilities (10) and (11) of a homogenous irredundant fleet of UAV are shown in Fig. 4.

The homogenous redundant UAV fleet can be interpreted as the k–out-of–n system (Fig.5). In this case the structure of UAV fleet is conditionally divided into two fleets: the main fleet and the redundant fleet. The main fleet is formed by the k UAVs which must have a sufficient level of performance for the mission implementation. The redundant fleet consists of (n - k) UAVs, which can replace the failed or degraded UAVs for successful implementation of a mission. This structure is typical for hot stable redundancy. The availability of the homogenous UAV fleet for hot stable redundancy with decentral control according to (4) and (6) is:

$$\begin{aligned} A^{(j)}_{HoRD} &= \Pr\left\{\bigvee\nolimits_{Q_k} \bigwedge\nolimits_{w=1}^{k} x_{i_w} \geq j\right\} = \\ &= \sum\nolimits_{v=k}^{n} \binom{n}{k} \cdot \left(\sum\nolimits_{s=j}^{m-1} \tilde{p_s}\right)^{v} \cdot \left(\sum\nolimits_{z=0}^{j-1} \tilde{p_z}\right)^{n-v} \end{aligned} \tag{12}$$


A homogenous hot stable redundant UAV fleet with a decentral control

(a)


A homogenous hot stable redundant UAV fleet with a central control

(b)

FIGURE 5. **Homogenous redundant UAV fleet with decentral (a) and central (b) control.**

and for the UAV fleet with central control:

$$\begin{aligned} A^{(j)}_{HoRC} &= \Pr\left\{\left(\bigwedge\nolimits_{x=1}^{n} x_i\right) x_{n+1} \geq j\right\} \\ &= \left(\sum\nolimits_{v=k}^{n} \binom{n}{k} \cdot \left(\sum\nolimits_{s=j}^{m-1} \tilde{p_s}\right)^{v} \cdot \left(\sum\nolimits_{z=0}^{j-1} \tilde{p_z}\right)^{n-v}\right) \\ &\cdot \left(\sum\nolimits_{r=j}^{m-1} \tilde{p_r}\right), \end{aligned} \tag{13}$$

where x_i $(i = 1, \ldots, n)$ is UAV i of fleet and x_{n+1} is central control unit; $\tilde{p_s}, \tilde{p_z}$ and $\tilde{p_r}$ are the probabilities of states s, z and r of system components accordingly (s, z, $r = 0, \ldots, m - 1$); $j = 1, \ldots, m - 1$.

The calculation of the availabilities (12) and (13) of a homogenous redundant fleet of UAVs is illustrated by pseudocode in Fig.6.

The heterogeneous structure of the UAV fleet is formed by UAVs of different properties therefore the UAV i of this fleet has unique value of probability for state s, which is $p_{i,s}$. Let us consider the similar structures for this fleet and the first of them is heterogeneous irredundant fleet of UAVs (Fig.7). This

```
// The calculation of $A^{(j)}_{HoRD}$
Initial data:
   $n$ – number of UAVs;
   $m$ – number of states of UAVs and fleet;
   $j$ – performance level $j$ of the UAV fleet;
   $k$ = number of operated UAVs
   $p_0$, …, $p_s$, …, $p_{m-1}$ – the probabilities of UAV states 0, .., $s$,.., $m$-1;

// Calculation of the probability of state $j$ from all possible states $j$ of UAV fleet for different
   combination of operated UAVs
   sumF = 0; //sumF – probability of failed UAV for state $j$
   sumO = 0;// sumO – probability of operated UAV for state $j$
   $s$ = 0;
   do { sumF= sumF + $p_s$ ; $s$++;}  while ($s$ < $j$);
   $s$ = $j$;
   do { sumO = sumO + $p_s$ ; $s$++;}  while ($s$ < $m$);

// Calculation of availability
   $A^{(j)}_{HoRD}$ = 0;

  do per each $v$ (where $v$ = $k$,…, $n$)
   {
// Calculation of number $Q$ of all possible states $j$ for v operated UAVs
   $Q$ = factorial(n)/(factorial($n$-$v$)*factorial($v$));
   $A^{(j)}_{HoRD}$= $A^{(j)}_{HoRD}$ + $Q$ * sumO^$v$ * sumF^($n$ – $v$) ; $v$++}
```

(a)

```
// The calculation of $A^{(j)}_{HoRC}$
Initial data:
   $n$ – number of UAVs;
   $m$ – number of states of UAVs and fleet;
   $j$ – performance level $j$ of the UAV fleet
   $k$ = number of operated UAVs
   $p_0$, …, $p_s$, …, $p_{m-1}$ – the probabilities of UAV/control unit states 0, .., $s$,.., $m$-1;

// Calculation of the probability of state $j$ from all possible states $j$ of UAV fleet for different
   combination of operated UAVs
   sumF = 0; //sumF – probability of failed UAV for state $j$
   sumO = 0;// sumO – probability of operated UAV for state $j$ or probability of working state of control
               unit
   $s$ = 0;
   do { sumF= sumF + $p_s$ ; $s$++;}  while ($s$ < $j$);
   $s$ = $j$;
   do { sumO = sumO + $p_s$ ; $s$++;}  while ($s$ < $m$);

// Calculation of availability
   $A^{(j)}_{HoRD}$ = 0;

  do per each $v$ (where $v$ = $k$,…, $n$)
   {
// Calculation of number $Q$ of all possible states $j$ for v operated UAVs
   $Q$ = factorial(n)/(factorial($n$-$v$)*factorial($v$));
   $A^{(j)}_{HoRD}$= $A^{(j)}_{HoRD}$ + $Q$ * sumO^$v$ * sumF^($n$ – $v$) ; $v$++}

// Calculation of availability with central control unit
   $A^{(j)}_{HoRD}$= $A^{(j)}_{HoRD}$ * SumO
```

(b)

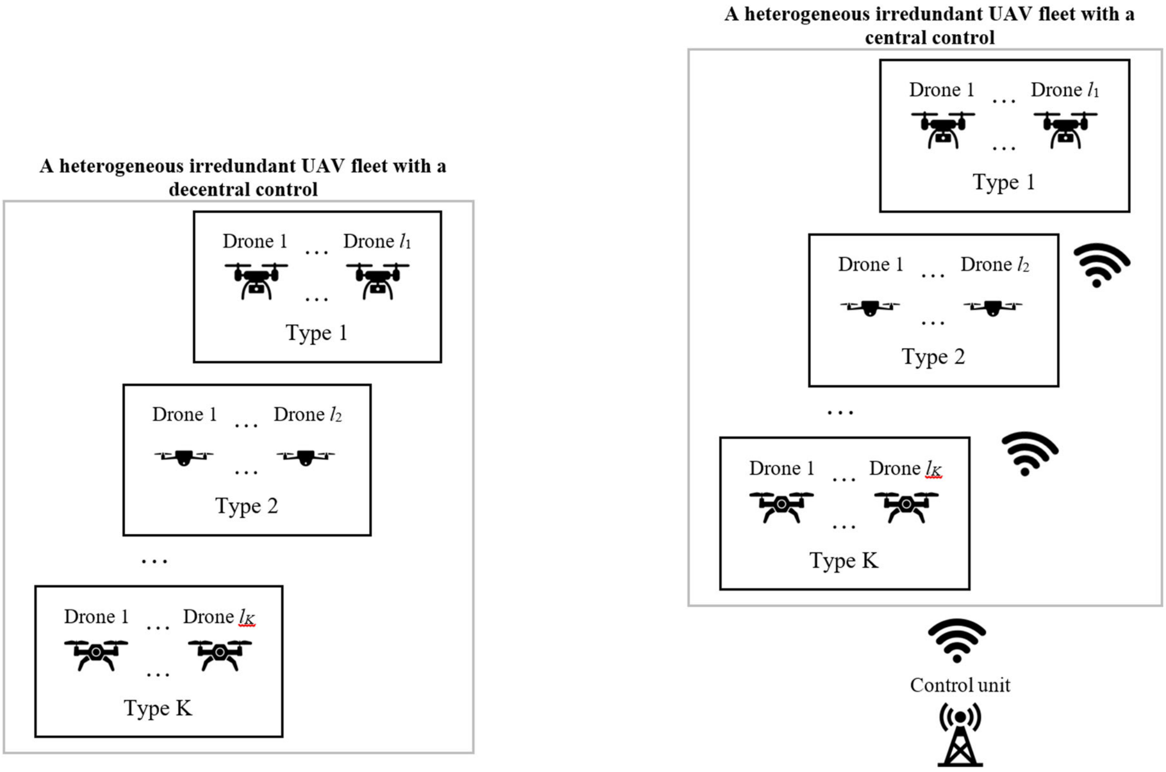
FIGURE 6. The calculation of availability of a homogenous redundant UAV fleet with decentral (a) and central (b) control.

fleet can be considered with the decentral and central control. The availabilities of these fleets are computed as (Fig.8):

$$A^{(j)}_{HeID} = \Pr\left\{\bigwedge\nolimits_{i=1}^{n} x_{\mathrm{i}} \geq \mathrm{j}\right\} = \\ = \sum\nolimits_{\phi(\mathbf{x})\geq j} p_{1,s_1}\cdot p_{2,s_2}\cdot\cdots\cdot p_{n,s_n} = \prod\nolimits_{i=1}^{n}\sum\nolimits_{s=j}^{m_i-1} p_{i,s} \qquad (14)$$

and

$$A^{(j)}_{HeIC} = \Pr\left\{\left(\bigwedge\nolimits_{i=1}^{n} x_{\mathrm{i}}\right) x_{n+1} \geq \mathrm{j}\right\} = \\ = \sum\nolimits_{\phi(\mathbf{x})\geq j} p_{1,s_1}\cdot p_{2,s_2}\cdot\cdots\cdot p_{n+1,s_{n+1}} = \\ = \prod\nolimits_{i=1}^{n+1}\sum\nolimits_{s=j}^{m_i-1} p_{i,s} \qquad (15)$$



(a)

(b)

FIGURE 7. Heterogeneous irredundant UAV fleet with decentral (a) and central (b) control.

```
// The calculation of $A^{(j)}_{HeID}$
Initial data:
   $n$ – number of UAVs;
   $m_i$ – number of states of the ith UAV
                                          ($i$ = 1,…, $n$)
   $j$ – performance level $j$ of the UAV fleet;
   $p_{i,0}$, …, $p_{i,s}$, …, $p_{i,m-1}$ – the probabilities of
      the ith UAV states 0, .., $s$,.., $m_i$-1;


// Calculation of availability
   $A^{(j)}_{HeID}$= 0
   do per each ith UAV ($i$ = 1,…, $n$)
   {   sumUAV=0; $s$ = $j$;
       do { sumUAV = sumUAV + $p_{i,s}$; $s$++;}
       while ($s$ < $m_i$);
     $A^{(j)}_{HeID}$= $A^{(j)}_{HeID}$= * sumUAV;
    }
```

(a)

```
// The calculation of $A^{(j)}_{HeIC}$
Initial data:
   $n$ – number of UAVs;
   $m_i$ – number of states of the ith UAV
                                          ($i$ = 1,…, $n$)
   $j$ – performance level $j$ of the UAV fleet;
   $p_{i,0}$, …, $p_{i,s}$, …, $p_{i,m-1}$ – the probabilities of
      the ith UAV states 0, .., $s$,.., $m$-1;
   $p_{n+1,0}$, …, $p_{n+1,s}$, …, $p_{n+1,m-1}$ – the probabilities of
      the control unit's states 0, .., $s$,.., $m_{n+1}$-1;

// Calculation of availability
// Calculation of UAVs availability
   $A^{(j)}_{HeID}$= 0
   do per each ith UAV ($i$ = 1,…, $n$)
   {   sumUAV=0; $s$ = $j$;
       do { sumUAV = sumUAV + $p_{i,s}$; $s$++;}
       while ($s$ < $m_i$);
     $A^{(j)}_{HeID}$= $A^{(j)}_{HeID}$= * sumUAV;
    }

// Calculation of control unit availability
   sumCU = 0; $s$ = $j$;
   do { sumCU = sumCU + $p_{n+1,s}$ ; $s$++;}
   while ($s$ < $m_{n+1}$);
     $A^{(j)}_{HeID}$= $A^{(j)}_{HeID}$ * sumCU;
```

(b)

FIGURE 8. The calculation of availability of a heterogenous irredundant UAV fleet with decentral (a) and central (b) control.

where x_i $(i = 1, \ldots, n)$ is UAV i of fleet and x_{n+1} is central control unit; $p_{i,s}$ is the probability of state s of the UAV i and $p_{n+1,s}$ is the probability of state s of the central control unit $(s = 0, \ldots, m_i - 1)$; $j = 1, \ldots, M - 1$.

The heterogeneous redundant fleet of UAVs is interpreted as the k−out-of−n system in the point of view of reliability analysis (Fig.9). It is similar with homogenous UAV redundant fleet. The availability of this fleet is like the availability of the homogenous redundant fleet, taking into account the differences of probabilities of state s for different UAVs. This type of fleet can be defined for the two structures:

- with the decentral control:

$$A_{HeRD}^{(j)} = \Pr\left\{\bigvee\nolimits_{Q_k} \bigwedge\nolimits_{w=1}^{k} x_{i_w} \geq j\right\} = \\ = \sum\nolimits_{v=k}^{n}\left(\sum\nolimits_{Q}\left(\prod\nolimits_{v}\sum\nolimits_{s=j}^{m_i-1} p_{i_v,s}\right) \cdot \left(\prod\nolimits_{z=n-v}\sum\nolimits_{s=0}^{j-1} p_{i_z,s}\right)\right) \quad (16)$$

- with the central control by the central control unit:

$$A_{HeRC}^{(j)} = \Pr\left\{(\bigvee\nolimits_{Q_k} \bigwedge\nolimits_{w=1}^{k} x_{i_w}) x_{n+1} \geq j\right\} = \\ = \sum\nolimits_{v=k}^{n}\left(\sum\nolimits_{Q}\left(\prod\nolimits_{v}\sum\nolimits_{s=j}^{m_i-1} p_{i_v,s}\right) \cdot \left(\prod\nolimits_{z=n-v}\sum\nolimits_{s=0}^{j-1} p_{i_z,s}\right)\right) \times \\ \times \left(\sum\nolimits_{r=j}^{m_{n+1}-1} p_{n+1,r}\right) \quad (17)$$

where Q is interpreted as the number of minimal paths of a system from the point of view of reliability analysis and defined in (5) as k−combinations; $p_{i_v,s}$ and $p_{i_z,s}$ are the probabilities of state s of the UAV i_v and i_z $(i_v, i_z = 1, \ldots, n)$; $p_{n+1,r}$ is the probability of state r of the central control unit $(r = 0, \ldots, m_{n+1} - 1)$.

The calculation of the availabilities (16) and (17) are illustrated in Fig. 10 by the pseudocode.

The availability calculation of considered structures of UAV fleets based on BSS structure function has been considered in [5] and summarized in Table 1. At the same time, the equations for the availability calculation of UAV fleet by the BSS structure function can be obtained based on (10) – (17) for $m = 2$ or $m_i = M = 2$ and $j = 1$.

IV. RESULT AND APPLICATION OF RELIABILITY ANALYSIS OF UAV FLEET OF DIFFERENT STRUCTURES

The proposed mathematical definition of availability of considered topologies of UAV fleet (10) – (17) can be used for a fleet evaluation. Below, in section A, the case study of a fleet a considered to illustrate the application of the proposed definitions of a fleet's availability. The calculation of the availability for fixed number of UAVs allows us to choose the most acceptable topology of fleet.

The analysis of different topologies of UAV fleet depending on the number of UAVs are considered below in section B.

TABLE 1. **Availability of UAV fleets of different structures based on BSS structure function.**

		Irredundant fleet	Hot stable redundant fleet
Homogenous UAV fleet	Decentral control	$A_{HoID} = p^n$	$A_{HoRD} = \sum_{v=k}^{n}\binom{n}{v} \cdot p^v \cdot q^{n-v}$
	Central control	$A_{HoIC} = p^{n+1}$	$A_{HoRC} = \left(\sum_{v=k}^{n}\binom{n}{v} \cdot p^v \cdot q^{n-v}\right) \cdot p_{n+1}$
Heterogenous UAV fleet	Decentral control	$A_{HeID} = \prod_i^n p_i$	$A_{HeRD} = \left(\sum_{v=k}^{n}\sum_Q(\prod_v p_i) \cdot (\prod_{n-v} q_i)\right)$
	Central control	$A_{HeIC} = \prod_i^{n+1} p_i$	$A_{HeRC} = \left(\sum_{v=k}^{n}\sum_Q(\prod_v p_i) \cdot (\prod_{n-v} q_i)\right) \cdot p_{n+1}$

The comparison of different topologies of UAV fleets is implemented based on this analysis.

A. CASE STUDY

Let us consider the example of the fleets of 5 UAVs $(n = 5)$ for the different introduced above structures and compute the availability for each of them and recommend the topology(s) depending on the best availability(s). As the first, let this fleet is defined as homogenous and is mathematically presented by MSS with $m = 3$. The homogenous type of the fleet needs in the definition of UAV state probabilities that are: $\tilde{p_0} = 0.08$, $\tilde{p_1} = 0.28$ and $\tilde{p_2} = 0.64$. In case of the central control of this fleet, the probabilities of the central control unit are defined as equal to the probabilities of the UAV states, i.e. $\tilde{p_0} = 0.08$, $\tilde{p_1} = 0.28$ and $\tilde{p_2} = 0.64$. The availabilities for the performance level 1 and 2 of the homogenous irredundant UAV fleet with the decentral control is computed according to (10) and they are:

$$A_{HoID}^{(1)} = \left(\sum\nolimits_{s=j}^{m-1}\tilde{p_s}\right)^n = \left(\sum\nolimits_{s=1}^{2}\tilde{p_s}\right)^5 = (\tilde{p_1} + \tilde{p_2})^5 = \\ = 0.92^5 = 0.6591 \quad (18)$$

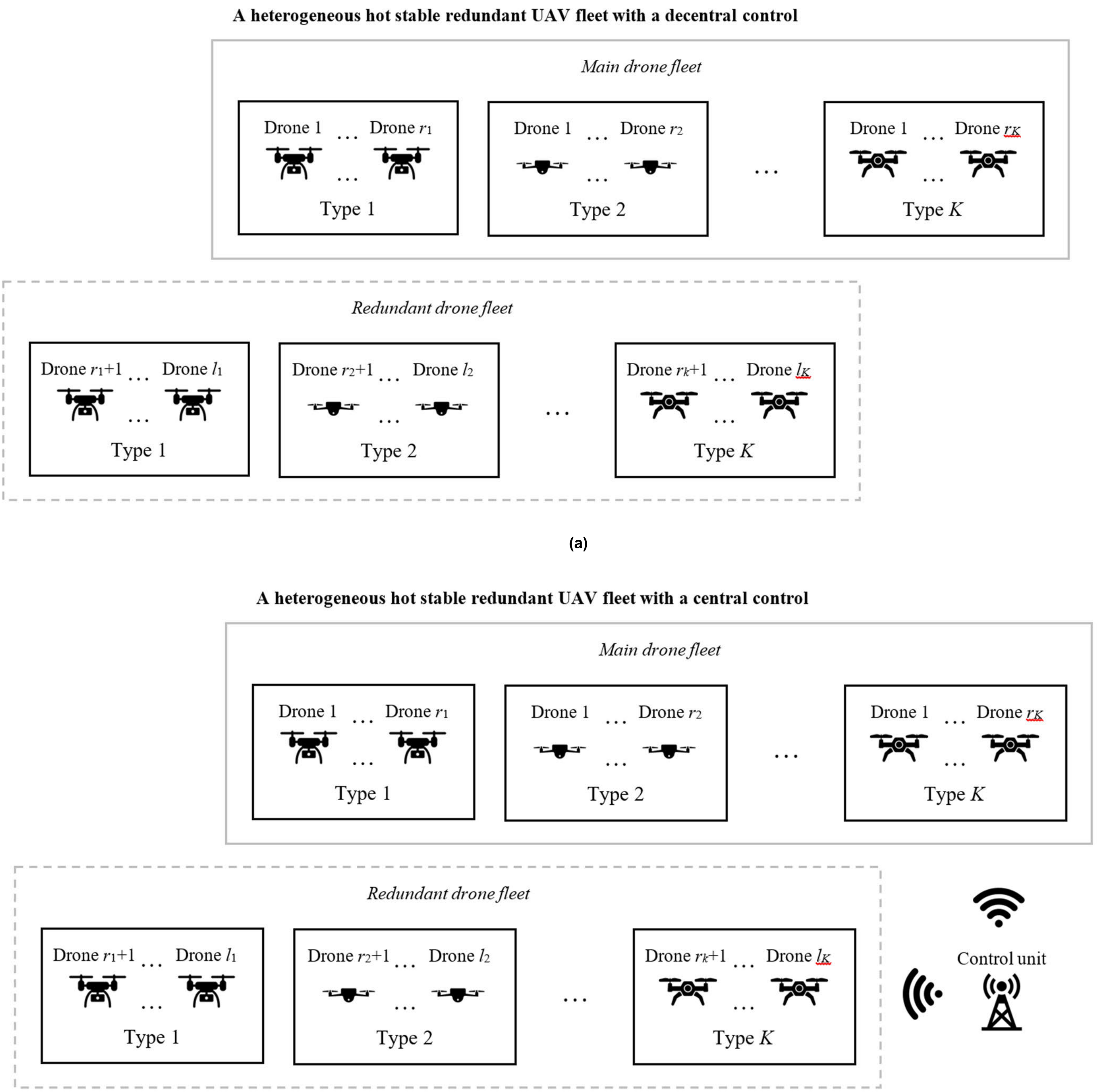
$$A_{HoID}^{(2)} = \left(\sum\nolimits_{s=j}^{m-1}\tilde{p_s}\right)^n = \left(\sum\nolimits_{s=2}^{2}\tilde{p_s}\right)^5 = \tilde{p_2}^5 \\ = 0.64^5 = 0.1073 \quad (19)$$

The availabilities of the first and the second performance levels of the homogenous irredundant UAV fleet with the central control that is implemented by the central control unit are computed according to (11):

$$A_{HoIC}^{(1)} = \left(\sum\nolimits_{s=j}^{m-1}\tilde{p_s}\right)^{n+1} = \left(\sum\nolimits_{s=1}^{2}\tilde{p_s}\right)^6 = (\tilde{p_1} + \tilde{p_2})^6 = \\ = 0.92^6 = 0.6064 \quad (20)$$

and

$$A_{HoIC}^{(2)} = \left(\sum\nolimits_{s=j}^{m-1}\tilde{p_s}\right)^{n+1} = \left(\sum\nolimits_{s=2}^{2}\tilde{p_s}\right)^6 = \tilde{p_2}^6 = \\ = 0.64^6 = 0.0687 \quad (21)$$



(a)

(b)

FIGURE 9. Heterogenous redundant UAV fleet with decentral (a) and central (b) control.

The comparison of the availabilities of homogenous irredundant UAV fleets with central and decentral control shows that the structure with the decentral control has best availability.

As the next, the homogenous redundant UAV fleets with the hot stable are considered. The availabilities for these fleets are computed according to (12) and (13) and shown in Table 2. Let us illustrate the calculation of these availabilities by the calculation of the availability of the performance level 1 of 3-out-of-5 type UAV fleet with decentral control:

$$A_{HoRD}^{(1)} = \sum\nolimits_{v=k}^{n} \binom{n}{v} \cdot \left(\sum\nolimits_{s=j}^{m-1} \tilde{p_s}\right)^{v} \cdot \left(\sum\nolimits_{z=0}^{j-1} \tilde{p_z}\right)^{n-v} =$$

$$= \sum\nolimits_{v=3}^{5} \binom{5}{v} \cdot \left(\sum\nolimits_{s=1}^{2} \tilde{p_s}\right)^{v} \cdot \left(\sum\nolimits_{z=0}^{0} \tilde{p_z}\right)^{5-v} =$$

$$= \binom{5}{3} \cdot (\tilde{\mathrm{p}_1} + \tilde{\mathrm{p}_2})^{3} \cdot \tilde{\mathrm{p}_0^2} + \binom{5}{4} \cdot (\tilde{\mathrm{p}_1} + \tilde{\mathrm{p}_2})^{4} \cdot \tilde{\mathrm{p}_0^1} +$$

```
// The calculation of $A_{HeRD}^{(j)}$
Initial data:
   $n$ – number of UAVs;
   $m_i$ – number of states of the $i$th UAV ($i$ = 1,…, $n$)
   $j$ – performance level $j$ of the UAV fleet;
   $p_{i,0}$, …, $p_{i,s}$, …, $p_{i,m-1}$ – the probabilities of the $i$th UAV states 0, .., $s$,.., $m_i$-1;

// Calculation of availability
   $A_{HeRD}^{(j)}$ = 0
//Calculation of availability for v operate UAVs
   do for v from $k$ to $n$
// Calculation of number $Q$ for v operated UAVs
   $Q$ = factorial(n)/(factorial($n$-$v$)*factorial($v$));
      do for each combination $Q$ of $v$ UAVs from $n$
      {prodO = 1  // prodO - probability of operated UAVs for performance level $j$
         do for all $w$ which is in set of operate UAVs
         {sumO$_w$ = 0  // sumO$_w$ – probability of failed the $w$th UAV for state $j$
          $s$ = 0;
          do { sumO$_w$= sumO$_w$ + $p_{w,s}$ ; $s$++;}  while ($s$ < $m_w$);}
       prodO = prodO * sumO$_w$}

       prodF = 1  // prodF - probability of fault UAVs for performance level $j$
          do for all $r$ which is not in set of operate UAVs
          {sumF$_r$ = 0  // sumF – probability of failed the $r$th UAV for state $j$
           $s$ = 0;
           do { sumF$_r$= sumF$_r$ + $p_{r,s}$ ; $s$++;}  while ($s$ < $j$);}
        prodF = prodF * sumF}
        $A_{HeRD}^{(j)}$ = $A_{HeRD}^{(j)}$ + (prodO * prodF)} }
```

(a)

```
// The calculation of $A_{HeRD}^{(j)}$
Initial data:
   $n$ – number of UAVs;
   $m_i$ – number of states of the $i$th UAV ($i$ = 1,…, $n$)
   $j$ – performance level $j$ of the UAV fleet;
   $p_{i,0}$, …, $p_{i,s}$, …, $p_{i,m-1}$ – the probabilities of the $i$th UAV states 0, .., $s$,.., $m_i$-1;
   $p_{n+1,0}$, …, $p_{n+1,s}$, …, $p_{n+1,m-1}$ – the probabilities of the control unit's states 0, .., $s$,.., $m_{n+1}$-1;

// Calculation of availability
   $A_{HeRD}^{(j)}$ = 0
//Calculation of availability for v operate UAVs
   do for v from k to n
// Calculation of number $Q$ for $v$ operated UAVs
   $Q$ = factorial(n)/(factorial($n$-$v$)*factorial($v$));
      do for each combination $Q$ of $v$ UAVs from n
      {prodO = 1  // prodO - probability of operated UAVs for performance level $j$
         do for all w which is in set of operate UAVs
         {sumO$_w$ = 0  // sumO$_w$ – probability of failed the $w$th UAV for state $j$
          $s$ = 0;
          do { sumO$_w$= sumO$_w$ + $p_{w,s}$ ; $s$++;}  while ($s$ < $m_w$);}
       prodO = prodO * sumO$_w$}

       prodF = 1  // prodF - probability of fault UAVs for performance level $j$
          do for all r which is not in set of operate UAVs
          {sumF$_r$ = 0  // sumF – probability of failed the $r$th UAV for state $j$
           $s$ = 0;
           do { sumF$_r$= sumF$_r$ + $p_{r,s}$ ; $s$++;}  while ($s$ < $j$);}
        prodF = prodF * sumF}
        $A_{HeRD}^{(j)}$ = $A_{HeRD}^{(j)}$ + (prodO * prodF)} }

// Calculation of control unit availability
   sumCU = 0; $s$ = $j$;
   do { sumCU = sumCU + $p_{n+1,s}$ ; $s$++;}
   while ($s$ < $m_{n+1}$);
      $A_{HeID}^{(j)}$= $A_{HeID}^{(j)}$ * sumCU;
```

(b)

FIGURE 10. The calculation of availability of a heterogeneous redundant UAV fleet with decentral (a) and central (b) control.

TABLE 2. **Availability of the homogenous redundant UAV fleet of 5 UAVs for different numbers of required functioning UAVs.**

The type of k-out-of-n system	The homogenous redundant UAV fleet with decentral control	The homogenous redundant UAV fleet with central control
1-out-of-5	$A^{(1)}_{HoRD} = 0.9999$, $A^{(2)}_{HoRD} = 0.9940$	$A^{(1)}_{HoRC} = 0.9199$, $A^{(2)}_{HoRC} = 0.6361$
2-out-of-5	$A^{(1)}_{HoRD} = 0.9998$, $A^{(2)}_{HoRD} = 0.9402$	$A^{(1)}_{HoRC} = 0.9198$, $A^{(2)}_{HoRC} = 0.6017$
3-out-of-5	$A^{(1)}_{HoRD} = 0.9955$, $A^{(2)}_{HoRD} = 0.7491$	$A^{(1)}_{HoRC} = 0.9159$, $A^{(2)}_{HoRC} = 0.4794$
4-out-of-5	$A^{(1)}_{HoRD} = 0.9456$, $A^{(2)}_{HoRD} = 0.4094$	$A^{(1)}_{HoRC} = 0.8700$, $A^{(2)}_{HoRC} = 0.2620$
5-out-of-5	$A^{(1)}_{HoRD} = 0.6591$, $A^{(2)}_{HoRD} = 0.1073$	$A^{(1)}_{HoRC} = 0.6064$, $A^{(2)}_{HoRC} = 0.0687$

TABLE 3. **The probabilities of the UAVs and control unit of heterogeneous fleet.**

Component of a fleet	Component states		
	0	1	2
UAV 1 (x_1)	0.08	0.28	0.64
UAV 2 (x_2)	0.08	0.28	0.64
UAV 3 (x_3)	0.05	0.95	--
UAV 4 (x_4)	0.05	0.95	--
UAV 5 (x_5)	0.10	0.45	0.45
The control unit (x_6)	0.05	0.40	0.55

$$+\binom{5}{5}\cdot(\tilde{\mathrm{p}_1}+\tilde{\mathrm{p}_2})^5\cdot \tilde{\mathrm{p}_0^0} =$$
$$= 10{\cdot}0.92^3\cdot 0.08^2 + 5{\cdot}0.92^4{\cdot}0.08 + 1{\cdot}0.92^5{\cdot}1 =$$
$$= 0.9955 \tag{22}$$

Analysis of the calculations of availability for the system under consideration in Table 2 shows that an increase in the number of required drones in the working state leads to a decrease in the availability of the fleet. This is typical for both availabilities of performance level 1 and performance level 2. It should be noted that the boundary values of k as $k = 1$ and $k = 5$ represent a parallel and series structure, respectively. The change of the structure of the homogenous redundant UAV fleets from decentral control to central control by the control unit causes a decrease in availability. It is explained that the central control unit is joined as a series component in the fleet.

Let us consider the next examples of availability evaluation of different structures for heterogeneous fleets. This fleet has three ($M = 3$) performance levels. Therefore according to (6) two availabilities for performance level 1 and performance level 2 should be computed. The probabilities of UAVs' states of this fleet are in Table 3.

As the first, we consider the heterogeneous irredundant fleet of UAVs. The availability of this fleet is computed according to (14) and (15) depending on type of control. The heterogeneous irredundant fleet of UAVs with decentral control based on UAVs' probabilities of states in Table 3 is computed as:

$$A^{(1)}_{HeID} = \prod_{i=1}^{n}\sum_{s=j}^{m_i-1} p_{i,s} =$$
$$= (p_{1,1}+p_{1,2})\cdot(p_{2,1}+p_{2,2})\cdot p_{3,1}\cdot p_{4,1}\cdot(p_{5,1}+p_{5,2}) =$$
$$= 0.92\cdot 0.92\cdot 0.95\cdot 0.95\cdot 0.90 = 0.6875 \tag{23}$$

$$A^{(2)}_{HeID} = \prod_{i=1}^{n}\sum_{s=j}^{m_i-1} p_{i,s}$$
$$= p_{1,2}\cdot p_{1,2}\cdot p_{3,1}\cdot p_{4,1}\cdot p_{5,2}$$
$$= 0.64\cdot 0.64\cdot 0.95\cdot 0.95\cdot 0.45 = 0.1663 \tag{24}$$

The use of the central control based on the central control unit changes the availabilities of the fleet as according to (15):

$$A^{(1)}_{HeIC} = \prod_{i=1}^{n+1}\sum_{s=j}^{m_i-1} p_{i,s} =$$
$$= (\mathrm{p}_{1,1}+\mathrm{p}_{1,2})\cdot(\mathrm{p}_{2,1}+\mathrm{p}_{2,2})\cdot \mathrm{p}_{3,1}\cdot \mathrm{p}_{4,1}$$
$$\cdot(\mathrm{p}_{5,1}+\mathrm{p}_{5,2})\cdot(\mathrm{p}_{6,1}+\mathrm{p}_{6,2}) =$$
$$= 0.92\cdot 0.92\cdot 0.95\cdot 0.95\cdot 0.90\cdot 0.95 = 0.6531 \tag{25}$$

$$A^{(2)}_{HeIC} = \prod_{i=1}^{n+1}\sum_{s=j}^{m_i-1} p_{i,s} =$$
$$= \mathrm{p}_{1,2}\cdot \mathrm{p}_{1,2}\cdot \mathrm{p}_{3,1}\cdot \mathrm{p}_{4,1}\cdot \mathrm{p}_{5,2}\cdot \mathrm{p}_{6,2} =$$
$$= 0.64\cdot 0.64\cdot 0.95\cdot 0.95\cdot 0.45\cdot 0.55 = 0.0915 \tag{26}$$

The availabilities of heterogeneous irredundant fleet of UAVs (23) – (26) shows that this structure have not high availability. Similarly with the homogenous structure, the addition of the central control unit decreases the fleet availability (25) – (26). The availability of the heterogeneous fleet can be changed using the redundant structures (Table 4). These availabilities are computed based on (16) and (17). For example, the availability of the performance level 1 for the fleet of the structure 3-out-of-5 with the decentral control are computed according to (16) as:

$$A^{(1)}_{HeRD}$$
$$= \sum_{v=k}^{n}\left(\sum_{Q}\left(\prod_{v}\sum_{s=j}^{m_i-1} p_{i_v,s}\right)\right.$$
$$\left.\cdot\left(\prod_{z=n-v}\sum_{s=0}^{j-1} p_{i_z,s}\right)\right) =$$
$$= \sum_{v=3}^{5}\left(\sum_{Q}\left(\prod_{v}\sum_{s=j}^{m_i-1} p_{i_v,s}\right)\right.$$
$$\left.\cdot\left(\prod_{z=n-v}\sum_{s=0}^{j-1} p_{i_z,s}\right)\right) =$$
$$= \sum_{10}\left(\prod_{v=3}\sum_{s=1}^{m_i-1} p_{i_v,s}\right)\cdot\left(\prod_{z=2}\sum_{s=0}^{1} p_{i_z,s}\right) +$$
$$+ \sum_{5}\left(\prod_{v=4}\sum_{s=1}^{m_i-1} p_{i_v,s}\right)\cdot\left(\prod_{z=1}\sum_{s=0}^{1} p_{i_z,s}\right) +$$

$$
\begin{aligned}
&+\left(\prod\nolimits_{v=5}\sum\nolimits_{s=1}^{m_i-1} p_{i_v,s}\right)=\\
&=\left(p_{1,1}+p_{1,2}\right)\left(p_{2,1}+p_{2,2}\right)\cdot p_{3,1}\cdot p_{4,0}\cdot p_{5,0}+\\
&+\left(p_{1,1}+p_{1,2}\right)\left(p_{2,1}+p_{2,2}\right)\cdot p_{4,1}\cdot p_{3,0}\cdot p_{5,0}+\\
&+\left(p_{1,1}+p_{1,2}\right)\left(p_{2,1}+p_{2,2}\right)\left(p_{5,1}+p_{5,2}\right)\cdot p_{3,0}\cdot p_{4,0}+\\
&+\left(p_{1,1}+p_{1,2}\right)\cdot p_{3,1}\cdot p_{4,1}\cdot p_{2,0}\cdot p_{5,0}+\\
&+\left(p_{1,1}+p_{1,2}\right)\cdot p_{3,1}\cdot\left(p_{5,1}+p_{5,2}\right)\cdot p_{2,0}\cdot p_{4,0}+\\
&+\left(p_{1,1}+p_{1,2}\right)\cdot p_{4,1}\cdot\left(p_{5,1}+p_{5,2}\right)\cdot p_{2,0}\cdot p_{3,0}+\\
&+\left(p_{2,1}+p_{2,2}\right)\cdot p_{3,1}\cdot p_{4,1}\cdot p_{1,0}\cdot p_{5,0}+\\
&+\left(p_{2,1}+p_{2,2}\right)\cdot p_{3,1}\cdot\left(p_{5,1}+p_{5,2}\right)\cdot p_{1,0}\cdot p_{4,0}+\\
&+\left(p_{2,1}+p_{2,2}\right)\cdot p_{4,1}\cdot\left(p_{5,1}+p_{5,2}\right)\cdot p_{1,0}\cdot p_{3,0}+\\
&+p_{3,1}\cdot p_{4,1}\cdot\left(p_{5,1}+p_{5,2}\right)\cdot p_{1,0}\cdot p_{2,0}+\\
&+\left(p_{1,1}+p_{1,2}\right)\left(p_{2,1}+p_{2,2}\right)\cdot p_{3,1}\cdot p_{4,1}\cdot p_{5,0}+\\
&+\left(p_{1,1}+p_{1,2}\right)\left(p_{2,1}+p_{2,2}\right)\cdot p_{3,1}\cdot(p_{5,1}+p_{5,2})p_{4,0}+\\
&+\left(p_{1,1}+p_{1,2}\right)\left(p_{2,1}+p_{2,2}\right)\cdot p_{4,1}\cdot(p_{5,1}+p_{5,2})p_{3,0}+\\
&+\left(p_{1,1}+p_{1,2}\right)\cdot p_{3,1}\cdot p_{4,1}\cdot(p_{5,1}+p_{5,2})\cdot p_{2,0}+\\
&+\left(p_{2,1}+p_{2,2}\right)\cdot p_{3,1}\cdot p_{4,1}\cdot(p_{5,1}+p_{5,2})\cdot p_{1,0}+\\
&+\left(p_{1,1}+p_{1,2}\right)\left(p_{2,1}+p_{2,2}\right)p_{3,1}\cdot p_{4,1}(p_{5,1}+p_{5,2})\\
&=0.004+0.004+0.0019+0.0066+0.0031+\\
&+0.0031+0.0066+0.0031+0.0031+\\
&+0.0052++0.0598+0.0598+0.0362+\\
&+0.0362+0.0764+0.6875=0.9968 \qquad (27)
\end{aligned}
$$

TABLE 4. Availability of the heterogeneous redundant UAV fleet of 5 UAVs for different numbers of required functioning UAVs.

The type of *k*-out-of-*n* system	The heterogenous redundant UAV fleet with decentral control	The heterogenous redundant UAV fleet with central control
1-out-of-5	$A_{HeRD}^{(1)}=0.9999$, $A_{HeRD}^{(2)}=0.9889$	$A_{HeRC}^{(1)}=0.9500$, $A_{HeRC}^{(2)}=0.5439$
2-out-of-5	$A_{HeRD}^{(1)}=0.9998$, $A_{HeRD}^{(2)}=0.9816$	$A_{HeRC}^{(1)}=0.9499$, $A_{HeRC}^{(2)}=0.5399$
3-out-of-5	$A_{HeRD}^{(1)}=0.9968$, $A_{HeRD}^{(2)}=0.8972$	$A_{HeRC}^{(1)}=0.9468$, $A_{HeRC}^{(2)}=0.4935$
4-out-of-5	$A_{HeRD}^{(1)}=0.9558$, $A_{HeRD}^{(2)}=0.5743$	$A_{HeRC}^{(1)}=0.9080$, $A_{HeRC}^{(2)}=0.3159$
5-out-of-5	$A_{HeRD}^{(1)}=0.6875$, $A_{HeRD}^{(2)}=0.1663$	$A_{HeRC}^{(1)}=0.6531$, $A_{HeRC}^{(2)}=0.0915$

According to the data in Table 4, the availability of the heterogenous redundant fleet availability decreases as the number of required functioning UAVs increases. The definitions of availability for the fleets of UAVs (10) – (17) allows us to consider the influence of number of drones for each of the considered structures.

The availability of irredundant homogenous (18) – (21) and heterogenous (23) – (26) UAV fleets is of approximately equal order. The fleet with decentral control has the best availability both for a homogeneous and heterogeneous fleet (18), (19), (23), (24). The comparison of the availabilities of the homogenous redundant fleet in Table 2 and the heterogenous redundant fleet in Table 4 shows that there are no principal differences between these topologies and the availabilities increase depending on the decreasing of the number of required active UAVs. The redundant fleet with the central control unit has less availability in comparison with the fleet with decentral control. Therefore, the redundant fleet with decentral control can be considered as best from the point of view of availability.

B. THE ANALYSIS OF THE AVAILABILITY OF UAV FLEETS OF DIFFERENT STRUCTURES

The availability of the UAV fleets depends on the structure of the fleet. Some of the typical structures are considered in the section III-B above. However, the availability of a UAV fleet is influenced not only by the structure but by the number of UAVs in the fleet. Consider below some estimates of the availability of the studied fleet structures depending on the size of the fleet (number of UAVs, n).

The evaluation of the homogenous fleet has been implemented for UAVs, which number in fleet n is change from 2 to 20. The number of this fleet performance level $m = 3$. The probabilities of UAVs and control unit working states have been defined randomly for state $1p_{i,1}$ from 0.100 to 0.700 and the probability of the fault state $p_{i,0}$ is chosen from set $\{0.050, 0.075, 0.100, \ldots, 0.200\}$. The important condition for the definition of the state probabilities is their sum is equal 1, therefore, $p_{i,2} = 1 - p_{i,1} - p_{i,0}$. The availability of the fleet is computed for fleet of $2, 3, \ldots, 20$ UAVs for each fixed set of probabilities. This availability calculation experiment is repeated 150 times for each different probability value, with fault probability values defined at 0.025 intervals as 0.050, 0.075, 0.100, …, 0.200. Then, for each n (the number of UAVs), the average availability value is calculated and shown on the graph.

The comparation of availabilities of homogenous irredundant UAV fleets with decentral and central control are in Fig. 11.

According to this study, the availability of a fleet with decentral control is better in comparison with a fleet with central control. The increase in the number of UAVs in the fleet causes a reduction in this difference, and with 15 UAVs this difference is practically absent.

The availability of a homogenous redundant UAV fleet depends on the number of operating UAVs k (Fig. 12).

Therefore, the analysis of this fleet availability depends on the number of UAVs and the specified number of working UAVs. This analysis shows that the increase in the number of worked UAVs for the fixed number of UAVs in the fleet results in a deterioration in availability. The availabilities in Fig. 12 are shown for the average dependencies, and this analysis was performed for sets of probabilities defined by similar way as for the homogenous irredundant fleets. The comparison of the availabilities of the performance levels $A^{(1)}$

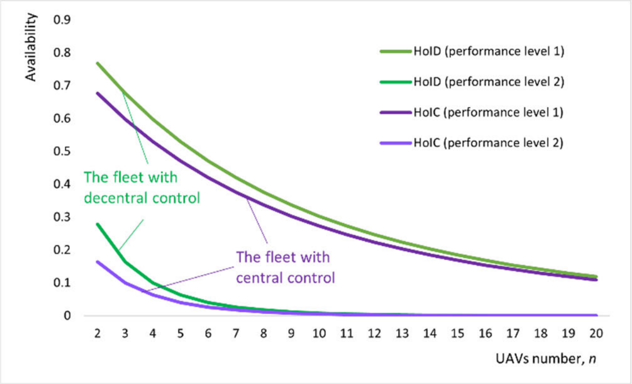


FIGURE 11. The availabilities of homogenous irredundant fleet of UAV.

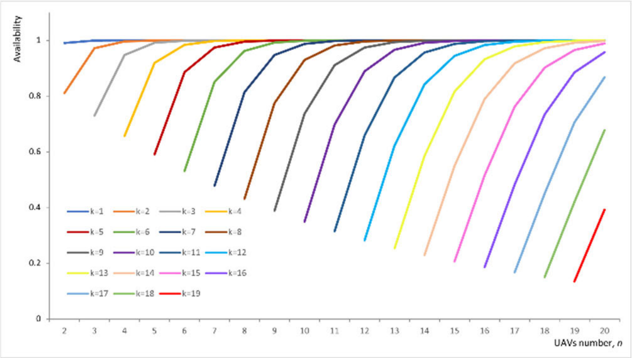


FIGURE 12. The availability $A^{(1)}$ of a homogenous redundant fleet of UAVs with decentralized control.

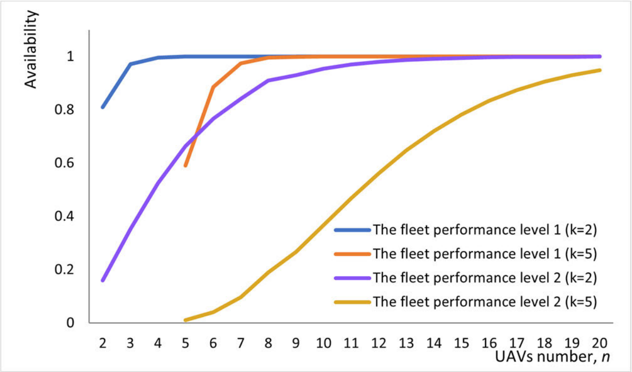


FIGURE 13. The availability $A^{(1)}$ and $A^{(2)}$ of a homogenous redundant fleets of UAVs with decentralized control (2-out-of-*n* and 5-out-of-*n*).

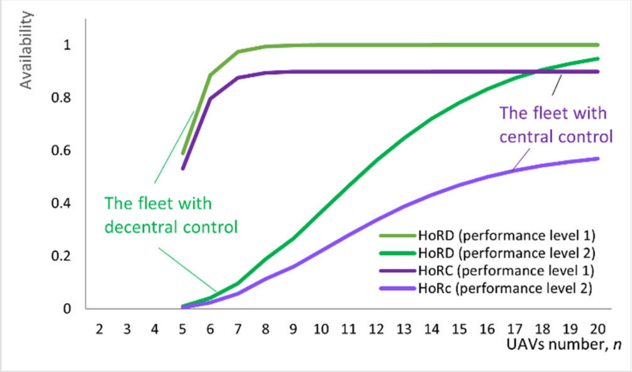


FIGURE 14. The availability $A^{(1)}$ and $A^{(2)}$ of a homogenous redundant fleets of UAVs with decentralized and central control (5-out-of−*n*).

and $A^{(2)}$ for homogenous redundant fleets 2-out-of−n and 5-out-of−n are shown in Fig. 13.

This diagram shows that the availability of the performance level 2 is less. It can be explained by the definition of the MSS availability (6): the availability of the performance level 1 includes the system states with performance level 1 and performance level 2. The curves in Fig. 14 illustrate the influence of the modification of the type of the fleet control.

The availability of the fleet with the control unit decreases according to evaluation based on the examples 5-out-of−n system.

The evaluation of the heterogeneous fleets of UAVs has been implemented in a similar way to the homogenous fleets. The number of this fleet performance level $M = 3$. The number of component states is $m_i \leq 3$. The difference between these experiments is the definition of the UAV state probabilities. The evaluation of a homogenous fleet needs the definition of the state probabilities for one UAV and these probabilities are used for other UAVs and control unit, in the case of the structure with central control. The evaluation of the heterogenous fleet needs the definition of the different sets of probabilities for each UAV. These probabilities are defined similarly to the definition of the state probabilities for UAV in a homogenous fleet: the probability of fault is randomly assigned from the set {0.050, 0.075, 0.100, …, 0.200} for each of UAVs in the fleet and the probability of state 1 id randomly indicated from 0.200 to 0.800 and probability of state 2 is computed as $p_{i,2} = 1 - p_{i,0} - p_{i,1}$.

The evaluation of the heterogenous fleet and its comparison with the homogenous fleet shows that the availability change for this fleet is similar (Fig. 15 and 16).

The interesting comparison can be done for the availability of fleet based on MSS and BSS. The availability of fleet based on BSS is computed by (7) and $p_i = p_{i,1} + p_{i,2}$ and $q_i = p_{i,0}$. This comparison is illustrated by Fig. 17 and Fig.18 for the fleet with decentral control.

The similar result is for the fleets with central control based on control unit. This experiment shows that the MSS should be used in case if the definition of the availabilities for all performance levels is important. The BSS should be used instead of MSS if the general availability for the performance level 1 is enough. The use of MSS in such case leads the redundance computation complexity of fleet analysis.

Also, for all structures, the availability value of performance level 1 is higher than performance level 2. This follows as expected from the definition of availability (6), so here it is more appropriate to use the concept of a probability of performance level, which was discussed, for example, in [33]. The probability of the performance level *j* of

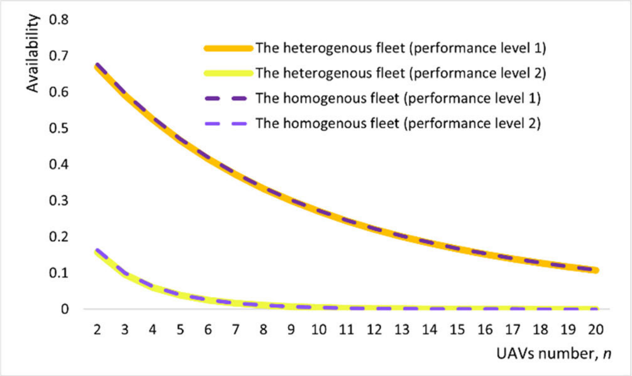


FIGURE 15. The availabilities $A^{(1)}$ and $A^{(2)}$ of homogenous and heterogenous irredundant fleets of UAV with the decentral control.

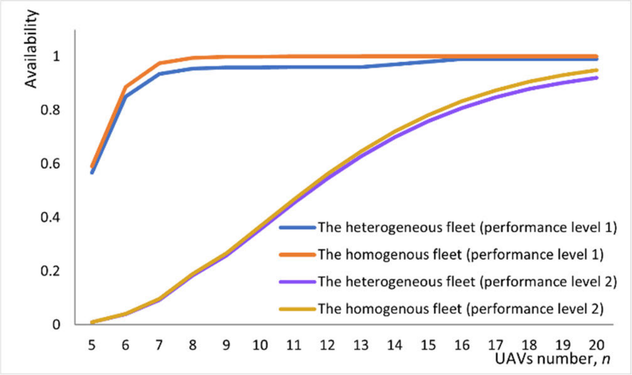


FIGURE 16. The availability $A^{(1)}$ and $A^{(2)}$ of a homogenous and heterogenous redundant fleets of UAVs with decentralized control (5-out-of-n).

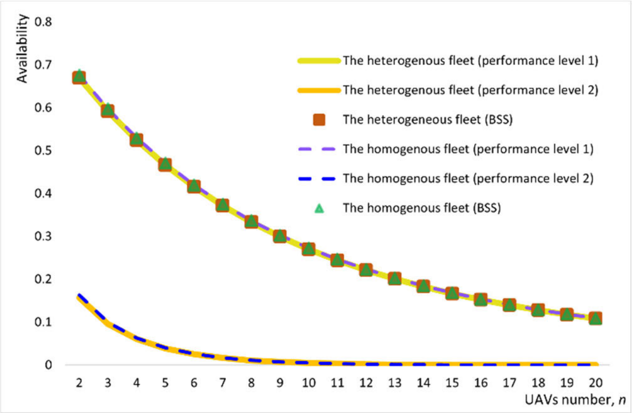


FIGURE 17. The availabilities of homogenous and heterogenous irredundant fleets of UAV with the decentral control computed based MSS and BSS.

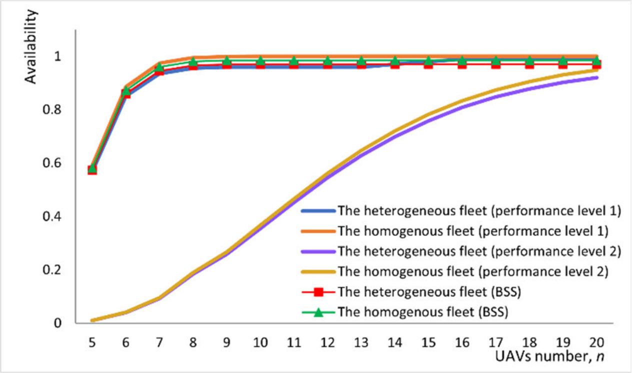


FIGURE 18. The availabilities of a homogenous and heterogenous redundant fleets of UAVs with decentralized control (5-out-of-n) computed based MSS and BSS.

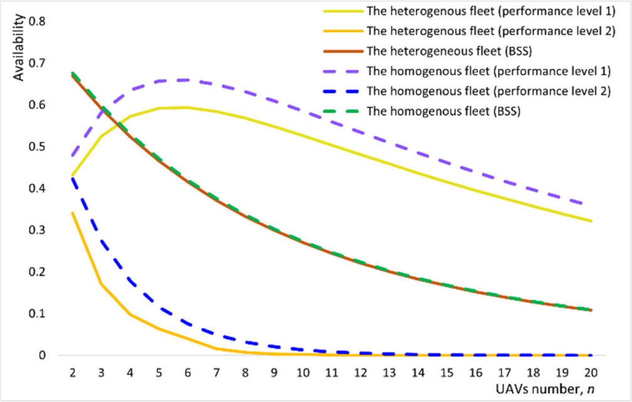


FIGURE 19. The probabilities of the performance levels of a homogenous and heterogenous irredundant fleets of UAVs with decentralized control computed based MSS and BSS.

MSS is defined as:

$$P^{(j)} = \Pr\{\phi(x) = j\}, j = 0, \ldots, M - 1. \tag{28}$$

The inappropriateness of using the concept of availability is confirmed by the diagrams in Fig. 17 and Fig. 18, where you can see that the availability for performance level 1 coincides with the availability calculated on the basis of the BSS. This result also determines the direction of further research. To further study the reliability of UAV fleets of various structures based on the mathematical model of the MSS, the probability of the performance levels of the system (28) will be used and an analysis of the importance of the fleet components will be performed using importance analysis methods. For example, the similar experiment for analysis of irredundant fleet with the decentral control depending to the number of UAVs in Fig.19 based on probabilities of performance levels (28). The comparison of the similar fleets availabilities (6) and probabilities of performance levels (28) shows that the second evaluation more detail and useful.

The computational complexity of the proposed algorithms for the calculation of UAV fleet availability based on MSS was evaluated. The software for this experimental study has been developed based on the proposed expression for availability calculation (10) – (15). The result of the evaluation of time for the calculation of the availability for the different types of UAV fleet is shown in Fig.20. The time of the algorithms running has been measured for systems of three performance levels ($m = 3$ or $M = 3$) and the calculation of the availabilities of the performance level $1(A^{(1)})$

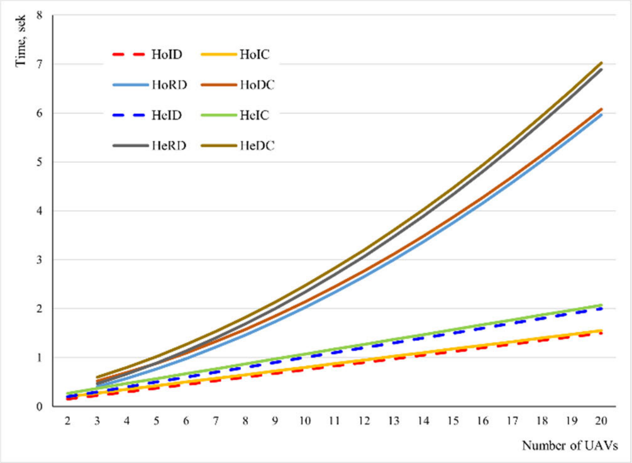


FIGURE 20. The time for the calculation of availabilities of UAV fleets.

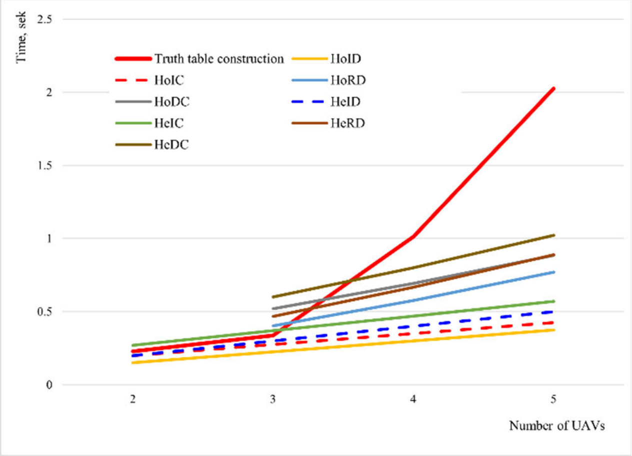


FIGURE 21. The comparison of time for the calculation of availabilities of UAV fleets base on proposed algorithms and structure function.

of the UAV fleets. The time of availability calculation for homogenous and heterogenous redundant fleets is computed as the average time for systems from 2-out-of$-n$ to $(n-1)-$out-of$-n$. The software application ran on a computer with Intel(R) Core(TM) i7-10750H CPU, 16GB, and MS Windows 11 operating system.

The comparison of the proposed algorithms for the calculation of availabilities of different types of UAV fleets has been done with the algorithm of UAV fleet availability computation based on the structure function, which is considered in [19], [33]. The calculation of the UAV fleet availability based on the structure function typical representation considered in [19], [33] supposes the representation of the structure function in the form of the truth table. In this experimental study, we don't take into account time for the truth table generation. The result of the comparison is shown in Fig. 21. This comparison shows that the use of the proposed algorithms for the calculation of UAV fleet availability needs less time and this difference extremely increases depending on the number of UAVs in the fleet. This difference is already sufficient with five UAVs and the time for the availability computation based on the truth table of the structure function increases exponentially depending on the number of UAVs. The comparison with the calculation of the availability based on the truth table of the structure function has been chosen because it is similar initial representation of the system. Of course, the methods based on fault trees or Multi-Valued Decision Diagram (MDD) can be considered too. But in this case, the time for the development of these representations should be taken into account too.

V. DISCUSSION AND CONCLUSION

In this paper, an analysis of the UAV fleet is implemented based on MSS. Structural function of MSS (1) was used as a mathematical model. The analysis of UAV fleets is carried out depending on their structural characteristics, such as homogeneity/heterogeneity, type of control (decentralized/centralized), and redundancy. For each type of structure, the definitions of fleet availability and its calculation (10) - (15) are introduced. The case study presented in Section III-A illustrates the ease of using these definitions to calculate the availability of a UAV fleet depending on its structural characteristics. Availability calculations for a fleet of 5 UAVs show that fleets with decentral control have higher reliability in terms of structure (see Table 2 and Table 4). Expectedly, a fleet with redundancy has better availability values than an irredundant fleet.

An assessment of various UAV fleet structures based on the obtained availability definitions (10) - (15) is carried out in section IV-B. These estimates for all structures show a decrease in availability when using central fleet control. This result is due to the interpretation of central control as a system in which the control unit is serial, as presented in the studies [34], [35], [40]. At the same time, the influence of the central unit on a fleet availability decreases if number of UAVs is increased for irredundant fleet (for example, it is illustrated in Fig.11 for homogenous fleet). The difference between the availabilities of fleets under centralized and decentralized control is negligible for a small number of UAVs but increases with the number of UAVs in the fleet (for homogenous fleet it is shown in Fig. 13).

The availability of a redundant fleet depends on the number of required active UAVs (k) regardless of the type of fleet and the type of control: the increase in the number of required active UAVs (k) leads to a decrease in fleet availability. It is typical for a mathematical model of $k-$out-of$-n$ system which is used for the representation of a redundant fleet.

It should also be noted that according to the studies did not show a fundamental difference in the availabilities of homogeneous and heterogeneous fleets. There is undoubtedly a difference in comparing individual fleets (Table 2 and Table 4). However, this difference does not appear in analysing a large number of fleets (Fig.15, Fig.16, Fig.17, Fig.18).

Also, for all structures, the availability value of performance level 1 is higher than performance level 2. This follows as expected from the definition of availability (6), so here it is more appropriate to use the concept of a probability of performance level (28). It is the probability of the performance level that will be used in further studies of the UAV fleet, in particular, in the importance analysis of the principal components (UAVs and control unit) of the fleet.

REFERENCES

[1] R. I. Mukhamediev, A. Symagulov, Y. Kuchin, E. Zaitseva, A. Bekbotayeva, K. Yakunin, I. Assanov, V. Levashenko, Y. Popova, A. Akzhalova, S. Bastaubayeva, and L. Tabynbaeva, "Review of some applications of unmanned aerial vehicles technology in the resource-rich country," *Appl. Sci.*, vol. 11, no. 21, p. 10171, Oct. 2021, doi: 10.3390/app112110171.

[2] A. Kumar, D. Augusto de Jesus Pacheco, K. Kaushik, and J. J. P. C. Rodrigues, "Futuristic view of the Internet of Quantum Drones: Review, challenges and research agenda," *Veh. Commun.*, vol. 36, Aug. 2022, Art. no. 100487, doi: 10.1016/j.vehcom.2022.100487.

[3] M. Almeida, H. Hildmann, and G. Solmaz, "Distributed uav-swarm-based real-time geomatic data collection under dynamically changing resolution requirements," *Int. Arch. Photogramm., Remote Sens. Spatial Inf. Sci.*, vol. 2, pp. 5–12, Aug. 2017, doi: 10.5194/isprs-archives-xlii-2-w6-5-2017.

[4] M. R. Silva, E. S. Souza, P. J. Alsina, D. L. Leite, M. R. Morais, D. S. Pereira, L. B. P. Nascimento, A. A. D. Medeiros, F. H. C. Junior, M. B. Nogueira, G. L. A. Albuquerque, and J. B. D. Dantas, "Performance evaluation of multi-UAV network applied to scanning rocket impact area," *Sensors*, vol. 19, no. 22, p. 4895, Nov. 2019, doi: 10.3390/s19224895.

[5] E. Zaitseva, V. Levashenko, R. Mukhamediev, N. Brinzei, A. Kovalenko, and A. Symagulov, "Review of reliability assessment methods of drone swarm (Fleet) and a new importance evaluation based method of drone swarm structure analysis," *Mathematics*, vol. 11, no. 11, p. 2551, Jun. 01, 2023, doi: 10.3390/math11112551.

[6] C. Wang, X. Wang, L. Xing, Q. Guan, C. Yang, and M. Yu, "Efficient reliability approximation for large k-out-of-n cold standby systems with position-dependent component lifetime distributions," *Rel. Eng. Syst. Saf.*, vol. 240, Dec. 2023, Art. no. 109548, doi: 10.1016/j.ress.2023.109548.

[7] T. Aven, "Improving risk characterisations in practical situations by highlighting knowledge aspects, with applications to risk matrices," *Rel. Eng. Syst. Saf.*, vol. 167, pp. 42–48, Nov. 2017, doi: 10.1016/j.ress.2017.05.006.

[8] R. Puchalski and W. Giernacki, "UAV fault detection methods, state-of-the-art," *Drones*, vol. 6, no. 11, p. 330, Oct. 2022, doi: 10.3390/drones6110330.

[9] H. Fesenko, V. Kharchenko, and E. Zaitseva, "Evaluating reliability of a multi-fleet with a reserve drone fleet: An approach and basic model," in *Proc. Int. Conf. Inf. Digit. Technol. (IDT)*, Jun. 2019, pp. 128–132, doi: 10.1109/DT.2019.8813738.

[10] Y. Ping, Y. Ren, Z. Li, D. Yang, and C. Yang, "An effective hybrid method for analysis the large-scale reliability block diagram model," *Maintenance Rel.*, vol. 25, no. 3, Jul. 2023, Art. no. 169408, doi: 10.17531/ein/169408.

[11] E. Zaitseva, V. Levashenko, M. Kvassay, and V. Kharchenko, "Reliability evaluation of heterogeneous drone fleet by structure function based method," in *Proc. 30th Eur. Saf. Rel. Conf. 15th Probabilistic Saf. Assessment Manage. Conf.*, 2020, pp. 4883–4889, doi: 10.3850/978-981-14-8593-0_5145-cd.

[12] B. Natvig, "Multistate system reliability," in *Wiley Encyclopedia of Operations Research and Management Science*. Hoboken, NJ, USA: Wiley, Jan. 2011, doi: 10.1002/9780470400531.eorms0553.

[13] A. Khayyati and M. Pourgol-Mohammad, "Developing an efficient approach for unmanned aerial vehicle reliability analysis," in *Safety Engineering, Risk, and Reliability Analysis*, vol. 14. New York, NY, USA: American Society of Mechanical Engineers, Nov. 2020, doi: 10.1115/imece2020-24079.

[14] S. B. Nazarudeen and J. Liscouët, "State-of-the-art and directions for the conceptual design of safety-critical unmanned and autonomous aerial vehicles," in *Proc. IEEE Int. Conf. Auto. Syst. (ICAS)*, Aug. 2021, pp. 1–5, doi: 10.1109/ICAS49788.2021.9551158.

[15] T. de Camargo, M. Schirrmann, N. Landwehr, K.-H. Dammer, and M. Pflanz, "Optimized deep learning model as a basis for fast UAV mapping of weed species in winter wheat crops," *Remote Sens.*, vol. 13, no. 9, p. 1704, Apr. 2021, doi: 10.3390/rs13091704.

[16] H. Dui, C. Zhang, G. Bai, and L. Chen, "Mission reliability modeling of UAV swarm and its structure optimization based on importance measure," *Rel. Eng. Syst. Saf.*, vol. 215, Nov. 2021, Art. no. 107879, doi: 10.1016/j.ress.2021.107879.

[17] I. Kliushnikov, H. Fesenko, G. Fedorenro, S. Rudakov, V. Mikhalevskyi, and O. Kompaniiets, "Swarm of unmanned aerial vehicles as a multi-state queueing system with non-controlled and controlled degradation," in *Proc. 12th Int. Conf. Dependable Syst., Services Technol. (DESSERT)*, Athens, Greece, Dec. 2022, pp. 1–7, doi: 10.1109/DESSERT58054.2022.10018784.

[18] S. Yangyao, Z. Xinchen, Y. Tianxiang, and Z. Zijian, "Multi-state balance system reliability research considering load influence," *Rel. Eng. Syst. Saf.*, vol. 233, May 2023, Art. no. 109087, doi: 10.1016/j.ress.2023.109087.

[19] L. Xing and B. W. Johnson, "Reliability theory and practice for unmanned aerial vehicles," *IEEE Internet Things J.*, vol. 10, no. 4, pp. 3548–3566, Feb. 2023, doi: 10.1109/JIOT.2022.3218491.

[20] T. Pogorzelski and T. Zielińska, "Vision based navigation securing the UAV mission reliability," in *Advances in Intelligent Systems and Computing*. Cham, Switzerland: Springer, 2022, pp. 251–263, doi: 10.1007/978-3-031-03502-9_26.

[21] R. Schacht-Rodríguez, J.-C. Ponsart, C. D. García-Beltrán, and C. M. Astorga-Zaragoza, "Prognosis & health management for the prediction of UAV flight endurance," *IFAC-PapersOnLine*, vol. 51, no. 24, pp. 983–990, 2018, doi: 10.1016/j.ifacol.2018.09.705.

[22] S. Basavaraju, V. A. Rangan, and S. Rajgopal, "Unmanned aerial system (UAS) hazard identification, reliability, risk analysis & range safety," in *Proc. Int. Conf. Range Technol. (ICORT)*, Feb. 2019, pp. 1–5, doi: 10.1109/ICORT46471.2019.9069620.

[23] S. Gong, M. Wang, B. Gu, W. Zhang, D. T. Hoang, and D. Niyato, "Bayesian optimization enhanced deep reinforcement learning for trajectory planning and network formation in multi-UAV networks," *IEEE Trans. Veh. Technol.*, vol. 72, no. 8, pp. 10933–10948, Aug. 2023, doi: 10.1109/TVT.2023.3262778.

[24] B. Ma, Z. Liu, W. Zhao, J. Yuan, H. Long, X. Wang, and Z. Yuan, "Target tracking control of UAV through deep reinforcement learning," *IEEE Trans. Intell. Transp. Syst.*, vol. 24, no. 6, pp. 5983–6000, Jun. 2023, doi: 10.1109/TITS.2023.3249900.

[25] R. Mukhamediev, Y. Kuchin, K. Yakunin, A. Symagulov, M. Ospanova, I. Assanov, and M. Yelis, "Intelligent unmanned aerial vehicle technology in urban environments," *Communications in Computer and Information Science*. Cham, Switzerland: Springer, 2020, pp. 345–359, doi: 10.1007/978-3-030-65218-0_26.

[26] I. Kliushnikov, V. Kharchenko, H. Fesenko, E. Zaitseva, and V. Levashenko, "Reliability models of multi-state UAV-based monitoring systems: Mission efficiency degradation issues," in *Proc. Int. Conf. Inf. Digit. Technol. (IDT)*, Zilina, Slovakia, Jun. 2023, pp. 299–306, doi: 10.1109/idt59031.2023.10194443.

[27] Q. Feng, M. Liu, H. Dui, Y. Ren, B. Sun, D. Yang, and Z. Wang, "Importance measure-based phased mission reliability and UAV number optimization for swarm," *Rel. Eng. Syst. Saf.*, vol. 223, Jul. 2022, Art. no. 108478, doi: 10.1016/j.ress.2022.108478.

[28] Y. M. Pashchuk, Y. P. Salnyk, V. V. Pashkovskyi, Y. H. Zaiets, V.-M.-V. Miskiv, and O. P. Shkiliuk, "Method for structural optimization of avionics of unmanned aerial vehicle," *Math. Model. Comput.*, vol. 7, no. 2, pp. 373–388, 2020, doi: 10.23939/mmc2020.02.373.

[29] A. Tahir, J. Böling, M.-H. Haghbayan, H. T. Toivonen, and J. Plosila, "Swarms of unmanned aerial vehicles—A survey," *J. Ind. Inf. Integr.*, vol. 16, Dec. 2019, Art. no. 100106, doi: 10.1016/j.jii.2019.100106.

[30] W. T. Alshaibani, I. Shayea, R. Caglar, J. Din, and Y. I. Daradkeh, "Mobility management of unmanned aerial vehicles in ultra–dense heterogeneous networks," *Sensors*, vol. 22, no. 16, p. 6013, Aug. 2022, doi: 10.3390/s22166013.

[31] B. Floriano, G. A. Borges, and H. Ferreira, "Planning for decentralized formation flight of UAV fleets in uncertain environments with dec-POMDP," in *Proc. Int. Conf. Unmanned Aircr. Syst. (ICUAS)*, Jun. 2019, pp. 563–568, doi: 10.1109/ICUAS.2019.8797928.

[32] A. Sawalmeh, N. S. Othman, G. Liu, A. Khreishah, A. Alenezi, and A. Alanazi, "Power-efficient wireless coverage using minimum number of UAVs," *Sensors*, vol. 22, no. 1, p. 223, Dec. 2021, doi: 10.3390/s22010223.

[33] E. Zaitseva and V. Levashenko, "Reliability analysis of multi-state system with application of multiple-valued logic," *Int. J. Quality Rel. Manage.*, vol. 34, no. 6, pp. 862–878, Jun. 2017, doi: 10.1108/ijqrm-06-2016-0081.

[34] M. Campion, P. Ranganathan, and S. Faruque, "UAV swarm communication and control architectures: A review," *J. Unmanned Vehicle Syst.*, vol. 7, no. 2, pp. 93–106, Jun. 2019, doi: 10.1139/juvs-2018-0009.

[35] N. Nomikos, P. K. Gkonis, P. S. Bithas, and P. Trakadas, "A survey on UAV-aided maritime communications: Deployment considerations, applications, and future challenges," *IEEE Open J. Commun. Soc.*, vol. 4, pp. 56–78, 2023, doi: 10.1109/OJCOMS.2022.3225590.

[36] J. Morio, B. Levasseur, and S. Bertrand, "Drone ground impact footprints with importance sampling: Estimation and sensitivity analysis," *Appl. Sci.*, vol. 11, no. 9, p. 3871, Apr. 2021, doi: 10.3390/app11093871.

[37] R. C. Millar, L. Hashemi, A. Mahmoodi, R. W. Meyer, and J. Laliberte, "Integrating unmanned and manned UAVs data network based on combined Bayesian belief network and multi-objective reinforcement learning algorithm," *Drone Syst. Appl.*, vol. 11, pp. 1–17, Jan. 2023, doi: 10.1139/dsa-2022-0043.

[38] O. Tannous, L. Xing, P. Rui, M. Xie, and S. H. Ng, "Redundancy allocation for series-parallel warm-standby systems," in *Proc. IEEE Int. Conf. Ind. Eng. Eng. Manage.*, Dec. 2011, pp. 1261–1265, doi: 10.1109/IEEM.2011.6118118.

[39] D. Paddeu and G. Parkhurst, "The potential for automation to transform urban deliveries: Drivers, barriers and policy priorities," in *Advances in Transport Policy and Planning*. Amsterdam, The Netherlands: Elsevier, pp. 291–314, 2020, doi: 10.1016/bs.atpp.2020.01.003.

[40] R. Ming, R. Jiang, H. Luo, T. Lai, E. Guo, and Z. Zhou, "Comparative analysis of different UAV swarm control methods on unmanned farms," *Agronomy*, vol. 13, no. 10, p. 2499, Sep. 2023, doi: 10.3390/agronomy13102499.

ELENA ZAITSEVA (Member, IEEE) received the M.S. and Ph.D. degrees in computer science from the Belarus State University of Informatics and Radioelectronics, Minsk, Belarus, in 1989 and 1994, respectively. From 1996 to 2004, she was with Belarus State Economic University. Since 2004, she has been with the Department of Informatics, University of Žilina, Slovakia. Since 2016, she has been a Professor with the Department of Informatics. She is the author of three books and more than 100 articles. Her research interests include mathematical methods in reliability and safety analysis, classification problems, and algebra logic-based methods application in reliability evaluation of complex systems. She is a member of the Technical Committee of the European Safety and Reliability Association and the Chair of the Reliability Association Chapter of Czechoslovakia Section of IEEE.

VITALY LEVASHENKO (Member, IEEE) received the M.S. and Ph.D. degrees in computer science from the Belarus State University of Informatics and Radioelectronics, Minsk, Belarus, in 1989 and 1994, respectively. From 1998 to 2004, he was with Belarus State Economic University, Minsk. Since 2004, he has been with the University of Žilina, Slovakia. Since 2014, he has been a Professor with the Department of Informatics. He is the author of three books and about 100 articles. His research interests include data analysis, classification problems, and system reliability evaluation.

VLADIMIR MYSKO received the B.S. degree in computer technology and software from West Kazakhstan Innovation and Technology University, Uralsk, Kazakhstan. He is currently pursuing the master's degree in information technology with West Kazakhstan Agrarian-Technical University. He actively works in the fields of computer technology and software, with a strong focus on the application and development of emerging technologies. His topic of work is innovative research and practical solutions in software development.

STANISLAW CZAPP (Member, IEEE) received the M.S. degree from the Gdańsk University of Technology, Poland, in 1996, and the Ph.D. and D.Sc. degrees, in 2002 and 2010, respectively. He is currently a Professor with the Faculty of Electrical and Control Engineering, Gdańsk University of Technology. He is the author or coauthor of many articles, conference papers, and unpublished studies, such as designs and expert evaluations and opinions. He is an Expert of the SEP Association of Polish Electrical Engineers in Section 08 electrical installations and devices. His research and teaching interests include power systems, electrical installations and devices, electric lighting, and electrical safety.

DARKHAN ZHAXYBAYEV received the bachelor's and master's degrees in pedagogical sciences from Pavlodar State University named after S. Toraigyrov (Pavlodar), in 2014 and 2016, respectively, and the Ph.D. degree in information systems from L. N. Gumilev Eurasian National University, Astana, in 2023.

From 2016 to 2018, he was a Lecturer with the Department of Mathematics and Informatics, Pavlodar State University named after S. Toraigyrov. From 2021 to 2023, he was a Lecturer with the Higher School "Information Technology," West Kazakhstan Agrarian-Technical University named after Zhangir Khan, where he has been an acting Associate Professor and the Head of the Higher School "Information Technologies," since 2023. He is the author of more than 20 articles. His research interests include methods of automatic text processing, information resources, machine learning, meaningful access to knowledge and data, and information extraction from text.

• • •