Application of theory of functional stability for information technology of unmanned aerial group control

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Abstract

In the paper, the analysis of the possibility of applying the theory of functional stability to the recovery control of the UAV group using FANET technology in the interests of agriculture has been carried out. It is shown that to ensure functional stability it is necessary to create hardware or software redundancies. It is also shown the need to detect failures and consider the probability of being in the state, which characterizes the presence of redundancy and the ability to implement the recovery control, as an indicator of the functional stability of the system. The indicator of functional stability of the system in general under the condition of ability to perform the set tasks is formulated in the analytical form.

Keywords

UAV group, ground control station, FANET, functional stability, failure, hardware and software redundancies

1. Introduction

The scale of use of unmanned aerial vehicle (UAVs) in agriculture grows every year. UAVs perform a variety of tasks from traditional ones, such as monitoring or irrigating fields with fertilizers and chemicals (Figure 1 a), to up-to-date tasks - determining the normalized difference vegetation indices, NDVI (Figure 1 b), field multispectral imaging (Figure 1 c), 3D field modeling (Figure 1 d), Trichogramma dropping (Trichogramma is a small insect that feeds on parasite eggs in the larval stage), etc. Today it is time to solve more complex tasks, such as the complex use of UAVs, which move in a group to perform tasks.

1.1. Related works

One of the tools for providing a group flight is computer network technology (Figure 2). Computer network technologies have become widespread in everyday life. First, they featured mobility and self-organization on the plane – MANET appeared. Then their mobility and the number of nodes increased but remained on the plane, and VANET appeared. When hardware development allowed controlling the spatial movements, FANET emerged. In these networks, it became possible to coordinate the movement of UAVs in three-dimensional space, which is required to solve our problem but requires solving complex network models. The interaction of devices in a group is considered in works [1-3]. Apparently, such networks are heavily influenced by internal and external disturbances. Here are some

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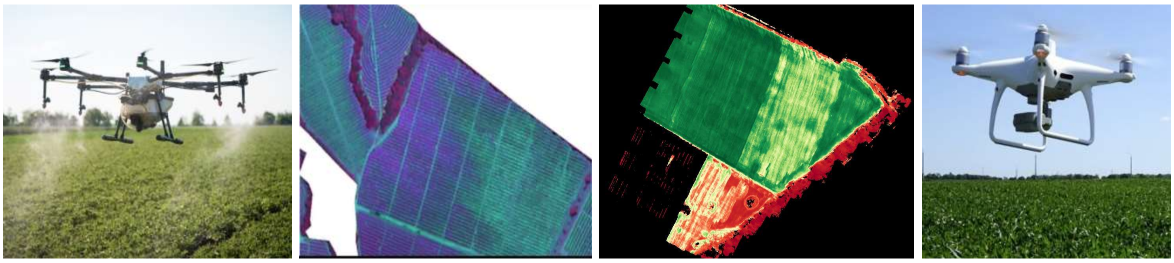
examples of external disturbances. Due to the presence of an atmospheric environment of information transfer between devices, there is a possibility of a loss of mutual visibility or communication in general. Moreover, today we observe an increasing number of attacks on UAVs by birds, animals, people.

Internal influences include reduced reliability and accelerated wear of onboard equipment when working in aggressive environments, etc. This indicates the need to take additional measures to improve the reliability of the assigned task implementation. There are many approaches to ensure the reliability, fault tolerance of devices and their systems; however, they have a number of shortcomings and, in our opinion, it is advisable to use the theory of functional stability of systems. Its feature is not only the ability to identify changes in the group, which are caused by external interference and failures of the devices themselves, but also to redistribute functions that cannot be performed by a particular device among others that are still functioning properly. These issues are considered in the works of professors O. Mashkov, O. Barabash, Yu. Kravchenko, M. Korobchynsky [4-7], etc. The essence of this theory is to keep an object or group of objects within a given field of states, control its performance and self-recovery. Therefore, the application of this theory is topical.



a b c d

Figure 1: Use of drones in agriculture: field irrigation (a); NDVI of vineyard plantation (b), multispectral imaging of field (c), 3D simulation of field (d)

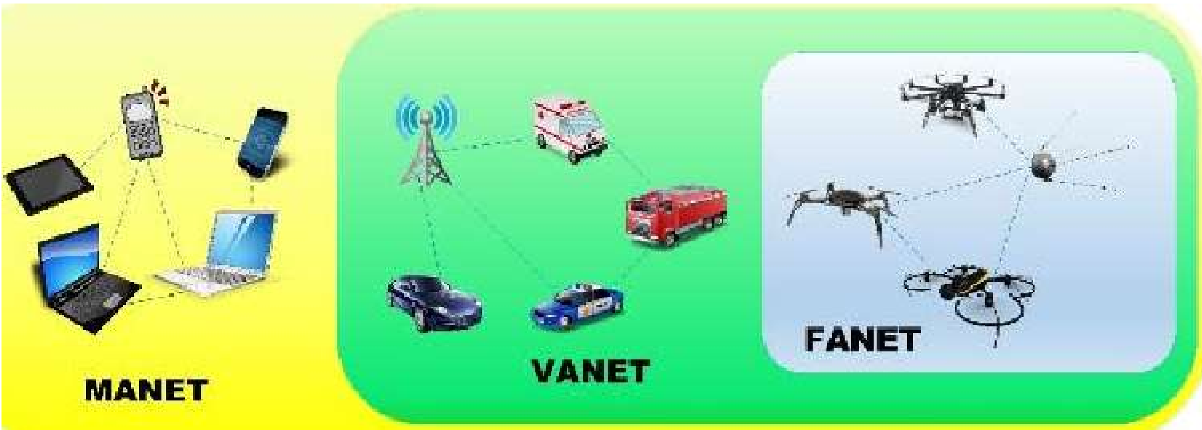


Figure 2: Evolution of computer network technology

2. Methods of functional stability theory

Schematically, the mutual location of the UAV group in the network is shown in Figure 3 [9-11]. As one can see, each UAV is supposed to have a connection with neighboring vehicles and with the GS control center directly or through another network node. Note that the main problems are the parameters of the medium: the conditions of propagation of radio waves, the distance between the devices, etc. In addition, problematic issues are complicated with solving problems that arise during the organization of the actual control of the UAV group: high mobility of system nodes, routing algorithms, different distances and maneuverability of aircraft, etc. The issue of direct group control for UAVs and vehicles is quite complex but it has a number of proposals for solutions, which are presented in [9-11]. It was proposed to consider a UAV as a "solid body", the flight geometric parameters of which are constant, their trajectory can be measured or interpolated in small domains where the connection between the devices was lost.

The mathematical model of the FANET can be written:

$$\mathrm{H}(t) = f(S, F, Y, X, t), \tag{1}$$

where $\mathrm{H}(t)$ – is the vector of network characteristics at the time t ($t \geq 0$); S – are structural parameters; F – are functional parameters; Y – is the network load; X – are environmental parameters; t – is the system operating time.

In [10, 12], these issues are covered in more detail.

Another important condition for the UAV networking is the presence of a minimum number of m^{min} working (undamaged) vehicles and ground control stations of the total number of N:

$$m = m^{min}. \tag{2}$$

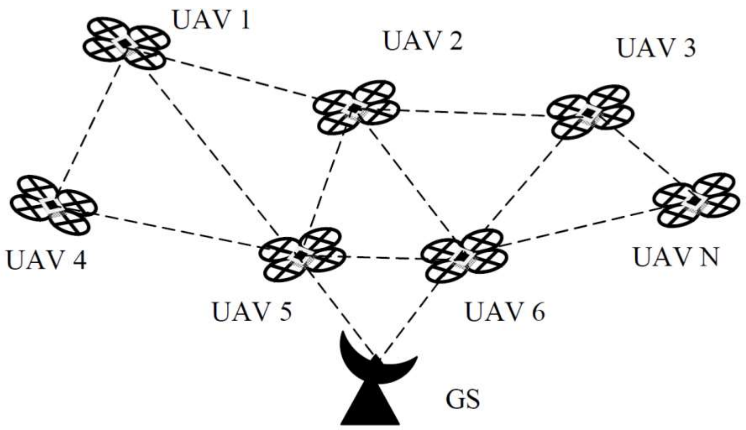


Figure 3: Self-organizing wireless network with UAV nodes

According to [4-8], the stability of functioning characterizes the behavior of the coordinates of undisturbed and disturbed motion of the system. Graphically, the condition of functionally stable control is shown in Figure 4 [4].

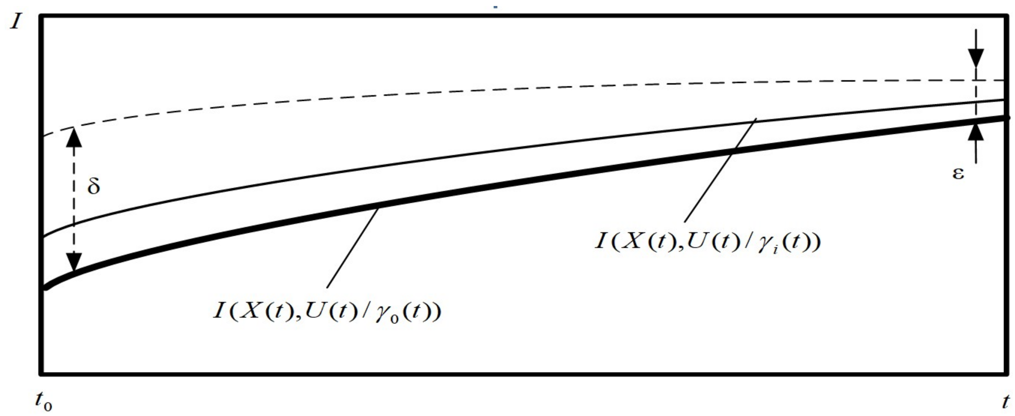


Figure 4: Conditions for ensuring functional stability

We can conclude that the control $U(t)$ with a given vector of observation of the system $H(t_i)$ of the object $X(t_i)$ with the chosen model of possible failures $\gamma_i(t)$ should provide a minimum of the chosen quality criterion $I(X(t_i), U(t_i) / H(t_i))$ under the imposed restrictions:

$$X(t) \in \Omega_X;$$
$$U(t) \in \Omega_U; \tag{3}$$
$$\gamma(t) \in \Omega_\gamma.$$

Thus, if at the initial moment t_0, failure leads to a deterioration of the quality of control within the positive ε, then the functionally stable control should ensure the quality of control not worse than δ, which depends on ε (Figure 4).

3. Results and discussions

3.1. Substantiation of the theory of functional stability indicators

In modern conditions, a UAV group is in a harsh environment (aggressive environment, the possibility of bird attack, etc.), as a result of which it is possible to disable or destroy individual vehicles. To study the functioning of the system in terms of stochastic effects on individual elements and on the system as a whole, we use the structural graph *G(Z, U)*. Let us select one point at the E-level, for example *2′* (Figure 5 a), and consider the model of characteristics of accuracy and stability of navigation for the point $z_{2'}$. In the radio visibility zone $z_{2'}$, there are two air objects (z_1, z_2) at the *Y*-level and the ground stations (z_{1H}, z_{2H}, z_{3H}, z_{4H}) at the *X*-level, which create a navigation field and a control field for the UAV group (levels *E* and *Y*). Each of the nodes has its own indicators of reliability and operability.

Let us simplify the scheme, preserving only the UAV and ground stations (GS), which are in sight for the device 2′, and rename them (Figure 5 b). It is also necessary to determine the probability ρ_i ($i = 1 - 5$) of the existence of each node.

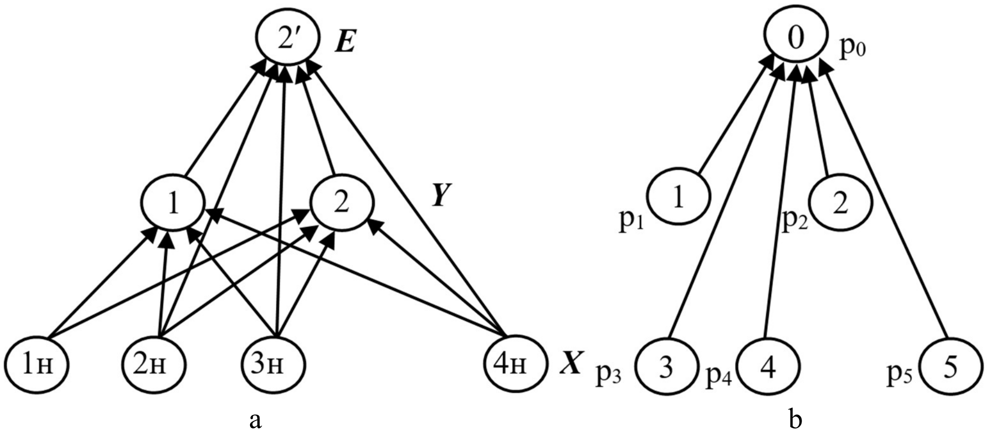


Figure 5: Element of graph *G*(*Z*,*U*) (a) and elementary graph for point z_{E2} (b)

The control task for the UAV (point 0) in the group can be solved in the presence of connection with other UAVs of the group (points 1 and 2), as well as with the ground stations (points 3, 4, 5):

$$m \geq m^{\min}. \tag{4}$$

The probability of solving the UAV control problem (point 0) can be expressed as the probability of the event of simultaneous observation of *m* objects (UAV groups and ground stations) out of *n* possible ones. For example, if we take *n = 5* and *m = 4*, then if we need to have 4 working UAVs that we observe, $C_m^n = 5$ combinations of working and inoperable objects can be made.

Assume that the ground stations operate independently of each other, then the probability of each combination will be defined as the product of the probabilities. All combinations, including those when the number of inoperable objects is insufficient, make up a group of incompatible events. The total probability of them is equals to "1" (excluding the requirements for the accuracy of the object location identification). It follows that the probability of solving the problem for combinations of *n* objects when at least *m* out of them are operable can be written as follows:

$$R_{m,n(\rho)} \sum_{r=m}^{n} P_{r,n(\rho)}, \quad \rho = \overline{1, N^E}, \tag{5}$$

where $P_{rn(\rho)} = \sum_k P_k(\rho)$ is the probability of simultaneous operability of the *r* objects out of *n* available.

Returning to our example, when 4 out of 5 objects are operable, we can write:

$$P_{4,5} = q_1\rho_2\rho_3\rho_4\rho_5 + \rho_1 q_2\rho_3\rho_4\rho_5 + \rho_1\rho_2 q_3\rho_4\rho_5 + \rho_1\rho_2\rho_3 q_4\rho_5 + \rho_1\rho_2\,\rho_3\rho_4 q_5;$$
$$P_{5,5} = \rho_1\rho_2\rho_3\rho_4\rho_5. \tag{6}$$

Each combination has its own variance of the root mean square error σ_i of the determining the consumer state vector at the point 0. Taking into account the probabilistic indicators, we obtain the distribution of the exact characteristics of the system (Table 1).

From Table 1 we can note:

- σ becomes probabilistic;
- for $m \geq m^{min}$, this system can be in 6 operable states, which allow performing assigned tasks;
- for $m < m^{min}$, the performance of assigned tasks is impossible.

Thus, we can state that the probability of controlling a UAV group with a given accuracy σ^{max} is the sum of combinations when

$$\sigma_i \leq \sigma^{max}, i = \overline{1,v}, \tag{7}$$

where $v = \sum_{r=m}^{n} C_r^n$ is a number of combinations.

Table 1

Table title

Combination	1	2	3	4	5	6	m < m^{min}
σ	σ_1	σ_2	σ_3	σ_4	σ_5	σ_6	∞
P_k	$P_{k(1)}$	$P_{k(2)}$	$P_{k(3)}$	$P_{k(4)}$	$P_{k(5)}$	$P_{k(6)}$	$1 - P_{4,5}$

We can also formulate in analytical form an indicator of the functional stability of the entire system, provided the assigned tasks are performed:

$$P(\Theta) = \sum_{i \in I} P_{k(i)}, \quad I = \left\{ i \middle| \sigma_{\rho,i} < \sigma^{max} \forall \rho \in \overline{1,N^E}, \quad N^E > 4, \quad \overline{i = 1,v} \right\}. \tag{8}$$

3.2. System elements probabilistic indicators

Note that the formula (8) obviously implies that the key factor for determining the proposed indicator of functional stability of the UAV group is the probability of being a specific objects in a certain state (1) $m \geq m^{min}$ which is significantly influenced by the external environment and technical condition of UAVs and ground stations.

In general, for the elements of the UAV group it is logical to write:

$$\rho_{ij} = \rho_{ij}^g \rho_{ij}^h \xi_{ij}, \tag{9}$$

where ρ_{ij}^g – is the probability of maintaining a working condition in case of damage (survivability); ρ_{ij}^h – is the probability of failure-free operation; ξ_{ij} – is the Boolean function, which equals 1 if the algorithm for the formation of recovery control includes it in the structure, otherwise 0.

For the ground control station, provided it is included in the structure, the value of p_{Xj} is determined by the product of indicators of operability (survivability) and reliability of the NPS (9).

For the UAV group, under similar conditions, the probabilities should also be multiplied by analogue indicators of survivability and reliability of UAVs, as well as by the probability of solving the navigation problem by the UAV itself:

$$\rho_{Yj} = \rho_{Yj}^g \rho_{Yj}^h \rho_{Yj}^{gn} \rho_{Yj}^{hn} \rho_{(Yj)}^{nab}, \tag{10}$$

where ρ_{Yj}^{gn}, ρ_{Yj}^{hn} – are operability (survivability) and reliability of the UAV; $\rho_{(Yj)}^{nab}$ is the probability of UAV navigation.

Based on the conditions of the problem to be solved by the UAV group, there are requirements for the accuracy of navigation (accuracy of approaching to a given point and compliance with the conditions of mutual location).

$$\sigma_\lambda \leq \sigma_\lambda^{\max}, \sigma_\varphi \leq \sigma_\varphi^{\max}, \sigma_h \leq \sigma_h^{\max}, \sigma_{v_x} \leq \sigma_{v_x}^{\max}, \sigma_{v_y} \leq \sigma_{v_y}^{\max}. \tag{11}$$

The fulfillment of the condition (11) is a random event, the probability of which P_h is called the probability of solving the problem of navigation with a given quality. There is a requirement for the value of this indicator

$$P_h > P_h^{\min}. \tag{12}$$

The condition (11) is necessary but insufficient for the functional stability of the UAV group and is *a feature of functional stability*. For example, a UAV group is able to get a field to perform specific tasks (irrigation, surveillance, protection, etc.)

Indeed, it is possible that the system will meet this condition in terms of accuracy and reliability, but only until an emergency situation, since it will not be able to react to its effects, i.e. the system will be operational but not functionally stable. For example, it will go to the area of irrigation or field monitoring, and UAVs will not be able to perform the tasks due to various damages or failures.

Thus, the quantitative assessment of functional stability still requires indicators that characterize the ability to improve the consequences of emergency situations, which, in turn, is determined by the presence of redundancy and the ability to control it. For example, in spite of damage or failure of a number of UAVs, the group both got to the area of use and performed its intended function (spraying, surveillance, protection, etc.).

Under the uncertainty conditions, this can be described as follows. Let A be an event that consists in the fact that the UAV group has the ability to improve the consequences of abnormal situations caused by the circumstances, then the probability of this event is $P(A)= P_p$.

Based on the previous considerations, we can write that

$$A = A_H \cap A_{kep}\,;\, A \cap (\overline{A_H} \cup \overline{A_{kep}}\,), \tag{13}$$

where A_H – is an event that consists in the presence of redundancy; A_{kep} – is an event that consists in the ability to control redundancy; $P(A_H) = P_h$ – is the probability of redundancy or available reserve in the system; $P(A_{kep}/A_H) = P_{kee}$ – is the probability that there is the possibility to control redundancy, or the probability of controlling redundancy.

The presence of redundancy in the system depends on many factors. Let us focus on structural redundancy, the essence of which is additional (reserve) radio navigation points or pseudo-satellites that are in the "hot" or "cold" reserve. We can write

$$P_h = P_h(N^X_{vid(\rho)}, N^Y_{vid(\rho)}, P^X_i, P^Y_j, F_k),\, i = \overline{1, N^X_{vid(\rho)}},\, j = \overline{1, N^Y_{vid(\rho)}}\,, \tag{14}$$

where $N^X_{vid(\rho)}$ – is the number of ground control stations in the consumer's field of vision; $N^Y_{vid(\rho)}$ – is the number of neighboring UAVs in the consumer's field of vision; P_i^X – is the probability of being the i^{th} ground control station in operable state; P_j^Y – is the probability of being the j^{th} ground control station in operable state; F_k– are other factors affecting redundancy.

$$P^X_i = P^X_i(P_i, P^G_i), \tag{15}$$

where P_i – is the probability of failure-free operation of the i^{th} ground control station over time t; P_i^G – is the probability of beeing the i^{th} ground control station in a survival condition over time t.

$$P^Y_j = P^Y_j(P_j, P^G_j), \tag{16}$$

where P_j – is the probability of failure-free operation of the j^{th} neighboring UAV over time t;P_j^G – is the probability of beeing the j^{th} neighboring UAV in a survival condition over time t.

The model (13-16) takes into account the influence of various factors on the redundancy, namely: the radio signal pass, the action of external factors, other obstacles, the reliability of components, their survivability, fault tolerance and others.

It is also advisable to use P_{cont} - a characteristic of the system's ability to use redundancy to improve the consequences of abnormal situations.

In some cases, the system operates for a short time and then for maintaining the required level of functional stability, it is advisable to have additional UAVs in the "hot" reserve. Then for the implementation of the algorithm of recovery control, we do not need to use P_{cont} and we consider $P_{cont} = 1$.

4. Conclusions

A feature of the functional stability of the UAV group is the ability to solve the problem of navigation by consumers with a given accuracy. The indicator of the functional stability of the pseudo-satellite radio navigation system is the probability of being in this state, which characterizes the presence of redundancy and the ability to implement recovery control to eliminate the consequences of abnormal situations.

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