Applying the Method of Categorical Analysis for Conceptual Design of an Automated Control System of a Group of Unmanned Aerial Vehicles

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Abstract. Conceptual design of automated control systems (ACS) is an important stage in their development and making. The miscalculations admitted during this stage, as a rule, couldn’t be compensated for in the subsequent stages of the project. At the same time, despite the great importance of this stage, nowadays there is no well-developed theory of conceptual design for ACS making and improvement. In generally, it all comes down to either using the prototype, or the talent and insight of the designer. In this article an attempt was made to develop a methodology for the conceptual design of ACS. A template for creating parametric concept of ACS with its subsequent detail through the use of the method of the categorical analysis is proposed. A method allows to form a fairly complete information space of control, taking into account all possible information interactions between groups of parameters based on the generated sequence of categorical subsets of the control process with their subsequent interpretation is described. An example of method using is demonstrated for development of the ACS concept by a group of unmanned aerial vehicles. A constructive scheme of control information, including data groups and relationships between them, is considered. An interpretation of categorical subsets, an example of detailing and data of the state of the control object and the definition of some information transformation procedures for one of the formed subsets are proposed.

1. Introduction

When any ACS is designed, a particularly important issue has always been and, apparently, will remain in the future, the issue of delineating the control space: determining the system of management goals, criteria for achieving them, indicators (characteristics) of the state of the control object. The answer to this question determines: what should be the appearance of the designed ACS, what will be the procedures and what methods of their implementation will be used. Miscalculations admitted at this (conceptual) design stage are likely to lead to failures in the development of promising ACSs. Neither the latest information technology means, nor multifunctional and high-performance programming environments can help. The more complex the automated control system is designed (management of an enterprise, military forces, defense of the state, the country as a whole), the more important is the conceptual design stage for obtaining an effective control system.

The procedure for the conceptual design of ACS includes the following stages or particular design tasks. First, it is the definition of the parameters of the "output" (external manifestations) of the control object; environment parameters; state parameters (measurement of changes from the point of view of
the subject of control) and control parameters. Second, it is the definition of procedures for converting the "output" parameters into state parameters, the formation of control parameters and the forecast of state changes. Third, it is the distribution of procedures by devices, include both controls and technical devices.

As we can see, the most important (decisive), from the point of view of the appearance formation of a promising ACS, are the first and second stages, where, in fact, the control space is formed. At the same time, the greatest conceptual difficulty here is the task of determining the parameters of the state - how the process of control the subject should be perceived, including the criteria and control strategies. Typically, this kind of design difficulty is resolved either on management practice which established, or on the basis of a prototype, or it is declared art and left to the mercy of the designer's talent. The first and second approaches are quite transparent, but the effectiveness of the automated control systems being created in them is provided only for yesterday. Tomorrow and the day after tomorrow are in doubt. The third approach - the talent and insight of the designer - is very effective in this respect, but, at the same time, it is a "thing in itself" which inaccessible for methodological description and widespread dissemination.

In the article, the inventive process of a talented designer of promising automated control systems is methodically regulated on the example of the development of the concept of an ACS by a group of unmanned aerial vehicles (UAVs) with using the method of categorical analysis.

The article describes a constructive scheme of control information, including group's data "output" conditions, the control and status; relations formalized between parametric groups, deployed at a set of points in time; data transformation procedures at control time. Within the framework of the constructive information scheme the group of state parameters of the control object on the basis of the interpretation of one of the categorical subsets of the integral process of control of a group of UAVs is detailed, data transformation procedures are proposed.

2. Constructive Scheme of Control Information of UAV Group

The main objective of the conceptual design of any complex systems, including and ACS is to bring the problem described qualitatively to a form structured, enables to conduct further quantitative research. The result of conceptual research should be the formation of the system structure describes the qualitative problem, the establishment of its boundaries in the form of relations with the environment, the allocation and interconnection of subsystems that affect the solution of the problem, the formulation of systemic tasks (tasks associated with relations in the system) [1].

There are two approaches to the synthesis of systems complement each other. These are ontological and constructive approaches.

In ontological design, the method of constructing concepts and deriving new concepts based on the accepted axioms is used [2]. In this case, the perfect way to define concepts will be the way of constructing conceptual constructions using axiomatic theories [3]. The mathematical apparatus of sets degrees is used to manipulate the structures of concepts [4].

Typical construct used with utilization of constructive approach for constructing conceptual models constructs an invariant with respect to the structures of various kind [5]. For example, a control loop in the constructive description of various control systems. Constructive approach involves the creation of a library of abstract constructs used as building blocks and at the conceptual description of complex systems [6].

In this article, a constructive approach uses an invariant template of management information for a typical ACS is used [7]. The figure shows a graphical interpretation of this template in the application to the ACS by a group of UAVs (figure 1).

The given conceptual information scheme includes the following data groups:

- discrete time values, $T$;
- discrete values of output parameters, $Y$;
- discrete values of the parameters of the operating conditions of the control object, $S$;
- discrete values of control parameters, $U$;
– discrete values of the control object state parameters, $X$.

The presentation of data in discrete form is due to the fact that the apparatus of set theory is used to describe them, and describe the relations between them and procedures for their transformation. Also, in practice, in the databases of real ACS, management data is present in a discrete form.

Discrete time values, $T$, are those values on the time axis that correspond to: the moments of updating the values of the output parameters, $Y$; the moments of updating the values of the parameters of the operating conditions, $S$; moments of application of managerial actions to the control object, $U$; the moments of occurrence of predicted consequences in the output parameters after the application of the corresponding controls.

Figure 1. Conceptual scheme of information in the ACS by the UAV group.
Output parameters, $Y$, mean data that comes to the system from available sources of information: radar stations (radar), airborne and ground-based electronic intelligence stations (EIS); onboard sighting and navigation systems (SNS), weapon control systems (WCS) and UAV reconnaissance systems, control points of the lower hierarchy level. These are: coordinates of current location of the UAV; parameters their orientation in space; kinematic parameters of their movement (speed, linear and angular acceleration); indicators of operating modes of onboard systems; characteristics of the functioning results.

Control parameters, $U$, are data generated by the control system to change the operation of the control object (UAV group) in order to achieve the desired state. The following can be considered as control parameters: the selected rational tactics of using the UAV group; target designation data; target allocation data; parameters of the reference trajectories of the group as a whole and of individual UAVs; parameters of operation of controls and onboard systems of UAVs.

The parameters of the operating conditions of the control object, $S$, are understood to be data that characterize the influence of the external environment the UAV group operates on the output parameters, restrictions on the state parameters forming the UAV control. As parameters of conditions can be considered: assessment of optical visibility and radar contrast of ground objects in different meteorological conditions, periods of the day and year, the nature of the underlying surface (the presence of landmarks, the state of the sea surface); the level of enemy radio-electronic interference, the state of the ground-based radio technical support system; wind strength and direction; zones of destruction of air defense systems (ADS) of the enemy; characteristics of survivability of enemy targets, etc.

The state parameters, $X$, are data that characterize the process of functioning of the control object (UAV group) in its perception by the control subject (ACS operator, commander, crew member of the leader aircraft of the mixed group). The following can be considered as state parameters: generalized and identified trajectory data; characteristics of real actions display of the UAV group in the parametric space of the implemented variant of use tactics; a degree of solution (effectiveness) of the assigned tasks; current risks and threat levels; warning signals, etc. The set of values of state parameters includes the following areas of the state space: area (border) of the limit-attainable states, $X_{\text{att}}$; the area of desired states, $X^*$, and the area of acceptable deviations from the desired states, $X_{\text{perm}}$. The area of the maximum attainable states, $X_{\text{att}}$, characterizes values of the object state parameters that can be theoretically realized under the established operating conditions, with a given control. The area of desirable states, $X^*$, includes values of the state parameters that characterize the purpose of using the UAV group. A wide range of target settings for group use of UAVs can be determined using a movable or fixed point in space and the structure of the placement of individual UAVs relative to this point. The specific formalization of the description of the purpose of the group's functioning depends on the aspects of management taken into account. The article proposes a method for ordering the space of considered aspects of management based on categorical analysis. The area of permissible deviations from the desired states, $X_{\text{perm}}$, is a set of permissible intervals of change in the values of the state parameters, are determined on the topology of the space of the parameters of the desired state. The mentioned topology and the values of the allowable intervals also depend on the considered aspects of control. In the conceptual design of an automated control system, the task of the designer is to take into account such aspects as fully as possible. This will make it possible in the future to easily adapt the ACS software to changing conditions and capabilities.

Various binary relations and transformation (mapping) procedures are established between the mentioned groups of data in the control system, presented by:

- binary relations between discrete values of time and values of conditions of functioning, $s^{\text{cond}}: T \rightarrow S$. These relationships can be defined by: sets of constants that are unchanged over specified periods of time; functions of changing the parameters of conditions over time in tabular or analytical form; differential equations (systems of differential equations);
– binary relations between discrete time values and values of output parameters, \( y: T \rightarrow Y \). These relations are also specified by means of sets of constants, or sets of tables, or analytical expressions, or differential equations (systems of differential equations);

– binary relations between discrete time values and values of control parameters, \( u: T \rightarrow U \). In other words, the law of control (changes in control parameters in time in a single time scale);

– sampling of combinations of desired values of state parameters, condition parameters and time values, \( G \subseteq X^* \times S \times T \), which is considered as a strategy (tactics) for using a group of UAVs (time transformation of the desired values of state parameters in specified use conditions). Such a sample is determined on base the decision of the operator (decision-maker (DM)) when the purpose and procedure for using the UAV group are described;

– binary relations between combinations of values of control parameters, parameters of conditions and time and the corresponding values of theoretically attainable state parameters, \( U \times S \times T \rightarrow X^{\text{att}} \). To establish this kind of relationship, as a rule, a model of the operation of the control object is used in various conditions with a variety of controls (model for calculating the range and duration of the flight, the effectiveness of reconnaissance, the effectiveness of destruction of objects, etc.);

– binary relations between combinations of values of state parameters, control parameters, parameters of conditions and time and the predicted values of output parameters corresponding to these combinations, \( y: U \times S \times T \times X \rightarrow Y \) (output forecast). To establish this kind of relationship, models of the output (observed) processes dynamics of the projected control system are used;

– binary relations between combinations of values of control parameters, state parameters, output parameters, condition parameters, time values at which the listed parameters were observed, and current time values and the restored values of state parameters corresponding to these combinations, \( q: U \times S \times Y \times X \times T^* \times T \rightarrow X \) (state recovery based on output data). To establish this kind of relationship, special models of output parameters transformation into state parameters are used, in line with the semantic content of the application process in relation to the decision maker.

The proposed conceptual information scheme can serve as the basis for further conceptual design of the ACS, in particular, for the development of a conceptual database model. However, the described results still contain quite a lot of uncertainties that require further detailing.

So, if for groups of output data and conditions it is already possible to form detailed lists of metrics, starting from the capabilities of existing telemetric and onboard information sensors, weather sensors, various types of reconnaissance, then the groups of status and control data are questionable. It is unclear exactly how to determine the tactics of using the group, how many and which tactics should be taken into account, what are the criteria for successfully solving problems, how exactly to measure the current state of a group of UAVs and individual UAVs in relation to the tasks being solved. These questions are usually answered by the designer. How complete or incomplete the adopted design decisions will be depends on the experience and breadth of knowledge of the decision maker, his talent as a designer. Is there any way we can help the designer in shaping this parametric space? At first glance, it seems that no, that this task is exclusively creative, not amenable to any kind of formalization. Nevertheless, according to the authors, it is possible. Without in any way detracting from the prerogative of the designer as a creator, it is possible to streamline his creative activity by transforming the integral problem of synthesis of a large dimension into a sequence of similar problems of a lower dimension. At the same time, without missing anything and not forgetting from the original "big" task. This approach is based on the categorical analysis method.

3. Detailing the Parameters of the State of a Controlled Group of UAVs Based on the Interpretation of Categorical Subsets

The method of categorical analysis consists in applying a deductive approach to the process of multilateral analysis of integrity [8]. The method is based on the statement of dialectics that any observable objects, systems, processes (integrity), the essence is the result of the interaction of the opposites contained in them [9]. The real world is contradictory. Its development occurs through the
emergence and resolution of contradictions. Therefore, the apparatus of thinking will be the more effective, the more it takes into account this property [8].

The opposites of the analyzed wholes are determined using the corresponding categorical pairs: "Whole - Particular"; "Present - Future"; "Defense - Attack" and so on. Categorical pairs necessarily force at every step of reasoning to identify and understand the essence of the corresponding contradictions.

In categorical analysis, the selected categorical pair divides the analyzed integrity into two parts in accordance with the content of this pair. Due to this, the analysis process becomes structured (focused). The application of several categorical pairs to the integrity provides the conditions for its multifaceted (multidimensional) analysis. For example, the use of three categorical pairs allows you to analyze an object from eight points of view (aspects).

For the categorical analysis of the process of using the UAV group, the authors used the following categorical pairs:

- "Control - Execution" ("C-E");
- "Whole - Part" ("W-P");
- "Goal - Means" ("G-M");
- "Defense - Attack" ("D-A");
- "Active - Passive" ("A*-P*").

The method of applying the listed categorical pairs to the analyzed process is as follows.

The process is divided into two parts: "C" and "E". The first part "C" considers the aspect of management, or, in other words, decision-making on changing the state of an object, the formation of an ideal state to which one needs to come, and a suitable (optimal) trajectory (in the broadest sense) of coming to this state. The second part "E" examines the aspect of the implementation of the formed management, taking into account the available possibilities, deviations from the ideal model of the object, the influence of the external environment.

Further, each of the formed two parts was divided into two parts with the help of the categorical pair "Whole - Part" ("W-P"). Four parts is received:

"C|W", "C|P", "E|P", "E|W".

Each of the four formed parts is characterized by a combination of two aspects of analysis. For example, a part or, in other words, a categorical subset, "C|W", offers to analyze the process of functioning of a group of UAVs in terms of managing the UAV group as a whole. The categorical subset, "C|P" - offers to analyze the process of functioning of UAVs group in terms of managing a separate UAV. The subsets "E|P" and "E|W" offers to analyze control and executing process in terms of the implementation of the control of a single UAV and UAV group as a whole.

The formed parts are divided to categorical subset by applying the remaining categorical pairs. These pairs are characterizing 32 points of view (aspects) of the analysis of information on the state of the UAV group. The table contains a list of the generated categorical subsets with a brief interpretation of their content in relation to the analyzed process (Table 1).

Table 1. Categorical subsets and interpretation of their content.

| Dedicated categorical subset | Content interpreting |
|------------------------------|----------------------|
| 1. "C|W|M|D|A**"             | Determination of the required application procedure for the whole UAV group when solves task of active defense (destroy or jamming ground (surface) and air targets in countering enemy's air defense system, reconnaissance of enemy forces with the active means). |
| 2. "C|W|M|D|P**"             | Determination of the required application procedure for the whole UAV |
3. "$C\vert W\vert M\vert A\vert A^*"

Determination of the required application procedure for the whole UAV group when solves task of active attack (destroy ground (surface) and air targets of enemy us main tasks, reconnaissance of enemy forces with the active means).

4. "$C\vert W\vert M\vert A\vert P^*"

Determination of the required application procedure for the whole UAV group when solves task of passive attack (using means of blocking enemy actions, including jamming ground (surface) and air objects (systems, complexes) of the enemy as the main tasks, reconnaissance of enemy with passive reconnaissance means).

5. "$C\vert W\vert G\vert D\vert A^*"

Determination of the permissible limits for parameters changing of the use order (criteria for the success of the application) for the whole UAV group when solves task of active defense (destroy or jamming ground (surface) and air targets in countering enemy’s air defense system, reconnaissance of enemy forces with the active means).

6. "$C\vert W\vert G\vert D\vert P^*"

Determination of the permissible limits for parameters changing of the use order (criteria for the success of the application) for the whole UAV group when solves task of passive defense (reduction efficiency of enemy air defenses due to passive methods (decoy system and visibility reducing, maneuvering, structure survivability (stability of onboard systems) in conditions of held influences) during battle, conducting reconnaissance of the enemy with passive reconnaissance means).

7. "$C\vert W\vert G\vert A^*"

Determination of the permissible limits for parameters changing of the use order (criteria for the success of the application) for the whole UAV group when solves task of active attack (destroy ground (surface) and air targets of enemy us main tasks, reconnaissance of enemy forces with the active means).

8. "$C\vert W\vert G\vert P^*"

Determination of the permissible limits for parameters changing of the use order (criteria for the success of the application) for the whole UAV group when solves task of passive attack (using means of blocking enemy actions, including jamming ground (surface) and air objects (systems, complexes) of the enemy as the main tasks, reconnaissance of enemy with passive reconnaissance means).

9. "$C\vert P\vert M\vert D\vert A^*"

Determination of the required application procedure for individual UAVs when solves task of active defense (destroy or jamming ground (surface) and air targets in countering enemy’s air defense system, reconnaissance of enemy forces with the active means).

10. "$C\vert P\vert M\vert D\vert P^*"

Determination of the required application procedure for individual UAVs when solves task of passive defense (reduction efficiency of enemy air defenses due to passive methods (decoy system and visibility reducing, maneuvering, structure survivability (stability of onboard systems) in conditions of held influences) during battle, conducting reconnaissance of the enemy with passive reconnaissance means).

11. "$C\vert P\vert M\vert A\vert A^*"

Determination of the required application procedure for individual
| No.  | Code       | Description                                                                 |
|------|------------|------------------------------------------------------------------------------|
| 12.  | "C|P|M|A|P*"  | Determination of the required application procedure for individual UAVs when solves task of active attack (destroy ground (surface) and air targets of enemy us main tasks, reconnaissance of enemy forces with the active means). |
| 13.  | "C|P|G|D|A*"  | Determination of the permissible limits for parameters changing of the use order (criteria for the success of the application) for individual UAVs when solves task of passive defense (reduction efficiency of enemy air defenses due to passive methods (decoy system and visibility reducing, maneuvering, structure survivability (stability of onboard systems) in conditions of held influences) during battle, conducting reconnaissance of the enemy with passive reconnaissance means). |
| 14.  | "C|P|G|D|P*"  | Determination of the permissible limits for parameters changing of the use order (criteria for the success of the application) for individual UAVs when solves task of passive defense (reduction efficiency of enemy air defenses due to passive methods (decoy system and visibility reducing, maneuvering, structure survivability (stability of onboard systems) in conditions of held influences) during battle, conducting reconnaissance of the enemy with passive reconnaissance means). |
| 15.  | "C|P|G|A|A*"  | Determination of the permissible limits for parameters changing of the use order (criteria for the success of the application) for individual UAVs when solves task of active attack (destroy ground (surface) and air targets in countering enemy's air defense system, reconnaissance of enemy forces with the active means). |
| 16.  | "C|P|G|A|P*"  | Determination of the permissible limits for parameters changing of the use order (criteria for the success of the application) for individual UAVs when solves task of passive attack (using means of blocking enemy actions, including jamming ground (surface) and air objects (systems, complexes) of the enemy as the main tasks, reconnaissance of enemy forces with the active means). |
| 17.  | "E|W|M|D|A*"  | Determination of the implemented parameters of the application procedure for the current conditions and the current state of the UAV and the control system of the UAV group for the whole UAV group when solves task of active defense (destroy or jamming ground (surface) and air targets in countering enemy's air defense system, reconnaissance of enemy forces with the active means). |
| 18.  | "E|W|M|D|P*"  | Determination of the implemented parameters of the application procedure for the current conditions and the current state of the UAV and the control system of the UAV group for the whole UAV group when solves task of passive defense (reduction efficiency of enemy air defenses due to passive methods (decoy system and visibility reducing, maneuvering, structure survivability (stability of onboard systems) in conditions of held influences) during battle, conducting reconnaissance of the enemy with passive reconnaissance means). |
| 19.  | "E|W|M|A|A*"  | Determination of the implemented parameters of the application procedure for the current conditions and the current state of the UAV and the control system of the UAV group for the whole UAV group |
when solves task of active attack (destroy ground (surface) and air targets of enemy us main tasks, reconnaissance of enemy forces with the active means).

20. "E|W|M|A|P*

Determination of the implemented parameters of the application procedure for the current conditions and the current state of the UAV and the control system of the UAV group for the whole UAV group when solves task of passive attack (using means of blocking enemy actions, including jamming ground (surface) and air objects (systems, complexes) of the enemy as the main tasks, reconnaissance of enemy with passive reconnaissance means).

21. "E|W|G|D|A*

Determination of the permissible limits of deviation from the specified parameters of the order of application (criteria for the success of the application), changed in accordance with the current conditions and state of the UAV and the control system of the UAV group, for the whole UAV group when solves task of active defense (destroy or jamming ground (surface) and air targets in countering enemy's air defense system, reconnaissance of enemy forces with the active means).

22. "E|W|G|D|P*

Determination of the permissible limits of deviation from the specified parameters of the order of application (criteria for the success of the application), changed in accordance with the current conditions and state of the UAV and the control system of the UAV group, for the whole UAV group when solves task of passive defense (reduction efficiency of enemy air defenses due to passive methods (decoy system and visibility reducing, maneuvering, structure survivability (stability of onboard systems) in conditions of held influences) during battle, conducting reconnaissance of the enemy with passive reconnaissance means).

23. "E|W|G|A|A*

Determination of the permissible limits of deviation from the specified parameters of the order of application (criteria for the success of the application), changed in accordance with the current conditions and state of the UAV and the control system of the UAV group, for the whole UAV group when solves task of active attack (destroy ground (surface) and air targets of enemy us main tasks, reconnaissance of enemy forces with the active means).

24. "E|W|G|A|P*

Determination of the permissible limits of deviation from the specified parameters of the order of application (criteria for the success of the application), changed in accordance with the current conditions, state of the UAV and the control system of the UAV group, for the whole UAV group when solves task of passive attack (using means of blocking enemy actions, including jamming ground (surface) and air objects (systems, complexes) of the enemy as the main tasks, reconnaissance of enemy with passive reconnaissance means).

25. "E|P|M|D|A*

Determination of the implemented parameters of the application procedure for the current conditions, the current state of the UAV and the control system of the UAV group, for the individual UAVs when solves task of active defense (destroy or jamming ground (surface) and air targets in countering enemy's air defense system, reconnaissance of enemy forces with the active means).
| Number | Expression | Description |
|--------|------------|-------------|
| 26.    | "E\[P\]M[D]\[P^*\]" | Determination of the implemented parameters of the application procedure for the current conditions, the current state of the UAV and the control system of the UAV group, for the individual UAVs when solves task of passive defense (reduction efficiency of enemy air defenses due to passive methods (decoy system and visibility reducing, maneuvering, structure survivability (stability of onboard systems) in conditions of held influences) during battle, conducting reconnaissance of the enemy with passive reconnaissance means). |
| 27.    | "E\[P\]M[A]\[A^*\]" | Determination of the implemented parameters of the application procedure for the current conditions, the current state of the UAV and the control system of the UAV group, for the individual UAVs when solves task of active attack (destroy ground (surface) and air targets of enemy us main tasks, reconnaissance of enemy forces with the active means). |
| 28.    | "E\[P\]M[A]\[P^*\]" | Determination of the implemented parameters of the application procedure for the current conditions, the current state of the UAV and the control system of the UAV group, for the individual UAVs when solves task of passive attack (using means of blocking enemy actions, including jamming ground (surface) and air objects (systems, complexes) of the enemy as the main tasks, reconnaissance of enemy with passive reconnaissance means). |
| 29.    | "E\[P\]G[D]\[A^*\]" | Determination of the permissible limits of deviation from the specified parameters of the flight program (criteria for the success of the application), which are modified in accordance with the current conditions and the state of the UAV, the control system of the UAV group for the individual UAVs when solves task of active defense (destroy or jamming ground (surface) and air targets in countering enemy’s air defense system, reconnaissance of enemy forces with the active means). |
| 30.    | "E\[P\]G[D]\[P^*\]" | Determination of the permissible limits of deviation from the specified parameters of the flight program (criteria for the success of the application), which are modified in accordance with the current conditions and the state of the UAV, the control system of the UAV group for the individual UAVs when solves task of passive defense (reduction efficiency of enemy air defenses due to passive methods (decoy system and visibility reducing, maneuvering, structure survivability (stability of onboard systems) in conditions of held influences) during battle, conducting reconnaissance of the enemy with passive reconnaissance means). |
| 31.    | "E\[P\]G[A]\[A^*\]" | Determination of the permissible limits of deviation from the specified parameters of the flight program (criteria for the success of the application), which are modified in accordance with the current conditions and the state of the UAV, the control system of the UAV group for the individual UAVs when solves task of active attack (destroy ground (surface) and air targets of enemy us main tasks, reconnaissance of enemy forces with the active means). |
| 32.    | "E\[P\]G[A]\[P^*\]" | Determination of the permissible limits of deviation from the specified parameters of the flight program (criteria for the success of the application), which are modified in accordance with the current conditions and the state of the UAV, the control system of the UAV group for the individual UAVs when solves task of passive attack (using means of blocking enemy actions, including jamming ground (surface) and air objects (systems, complexes) of the enemy as the main tasks, reconnaissance of enemy forces with the active means). |
conditions and the state of the UAV, the control system of the UAV group for the individual UAVs when solves task of passive attack (using means of blocking enemy actions, including jamming ground (surface) and air objects (systems, complexes) of the enemy as the main tasks, reconnaissance of enemy with passive reconnaissance means).

The above list of the analysis aspects of the functioning process of the UAV group can be further expanded with considering the processes of mutual influence of the formed units. For example, two parts: "C/W/G/D/A*" and "C/W/G/D/P*", form four types of processes:

- process of suppressing the forms of "passive" defense when increasing of the "active" defense capabilities: "C/W/G/D/A*" + = "C/W/G/D/P*";
- process of suppressing the forms of "active" defense when increasing of the "passive" defense capabilities: "C/W/G/D/A*" = "C/W/G/D/P*";
- process of mutual suppression when increasing of the “active” and “passive” defense capabilities: "C/W/G/D/A*" + + "C/W/G/D/P*";
- process of mutual reinforcement when increasing of the “active” and “passive” defense capabilities: "C/W/G/D/A*" ++ = "C/W/G/D/P*".

The final list of aspects of the analysis will be 1984 aspects with considering the processes of mutual influence of opposite parts. The potential possibilities of the categorical analysis method is very great for generating a variety of aspects. However, consideration is limited only to those aspects that are given in the table (Table 1). The state of the group parameters of the UAV is detailed using the aspects generated on the basis of the aspects. Detailed parameter results are shown for only one (first) categorical subset ("C/W/G/D/A") below.

The application procedure of UAVs group which solves task of enemy destroying and jamming (in case when these tasks are associated with solving basic tasks) can be determined using the following indexes (figure 2).

- coordinates of reference point location of the group in the established coordinate system. The coordinates are set using parametric functions, where the parameter is the path length of the group flight path, s:

$$
R(s) = (x^R(s) \ y^R(s) \ z^R(s))^T ,
$$

(1)

- speed of the reference point movement:

$$
\nu^R(s) = (x^R(s) \ y^R(s) \ z^R(s))^T
$$

(2)

- coordinates of individual UAVs relative to the reference point (in the coordinate system of the group's combat order):

$$
R_{\text{order}}(s) = (r_1(s) \ \ldots \ r_i(s) \ \ldots \ r_M(s)) = \begin{pmatrix}
  x_1(s) & \ldots & x_i(s) & \ldots & x_M(s) \\
  y_1(s) & \ldots & y_i(s) & \ldots & y_M(s) \\
  z_1(s) & \ldots & z_i(s) & \ldots & z_M(s)
\end{pmatrix},
$$

(3)

where $M$ is the number of UAVs in the group;

- ranges of fire (use of electronic warfare means) of UAVs group onboard systems in case of destroy of the $j$ -th means (object) of enemy air defense:

$$
L_{\text{fire}} = \begin{pmatrix}
  l_{1,1}^{\text{fire}} & \ldots & l_{1,j}^{\text{fire}} & \ldots & l_{1,N}^{\text{fire}} \\
  l_{2,1}^{\text{fire}} & \ldots & l_{2,j}^{\text{fire}} & \ldots & l_{2,N}^{\text{fire}} \\
  \vdots & \ddots & \vdots & \ddots & \vdots \\
  l_{M,1}^{\text{fire}} & \ldots & l_{M,j}^{\text{fire}} & \ldots & l_{M,N}^{\text{fire}}
\end{pmatrix},
$$

(4)

where $N$ is the number of air defense objects, the location of which makes it possible to attack (exert influence) on the UAV group;
Figure 2. Parameters of the application procedure of UAVs group which solves task of enemy destroying and jamming (in case when these tasks are associated with solving basic tasks).

- detection ranges of ground (sea) or air objects:

\[ L_{\text{lctn}} = \begin{pmatrix} l_{1,1}^{\text{lctn}} & \cdots & l_{1,j}^{\text{lctn}} & \cdots & l_{1,N}^{\text{lctn}} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ l_{M,1}^{\text{lctn}} & \cdots & l_{M,j}^{\text{lctn}} & \cdots & l_{M,N}^{\text{lctn}} \end{pmatrix}, \]  

(5)

- angles of rotation and angles that determine the size of the sectors of firing (jamming) of each UAV of the group:

\[ \Theta_{\text{fire}} = \begin{pmatrix} \theta_1^{\text{fire}} & \cdots & \theta_i^{\text{fire}} & \cdots & \theta_M^{\text{fire}} \end{pmatrix}^T, \]

(6)

\[ \Phi_{\text{fire}} = \begin{pmatrix} \phi_1^{\text{fire}} & \cdots & \phi_i^{\text{fire}} & \cdots & \phi_M^{\text{fire}} \end{pmatrix}^T, \]

(7)

- angles of rotation and angles that determine the size of the reconnaissance sectors of the air and ground (overwater) space of the UAV:

\[ \Theta_{\text{lctn}} = \begin{pmatrix} \theta_1^{\text{lctn}} & \cdots & \theta_i^{\text{lctn}} & \cdots & \theta_M^{\text{lctn}} \end{pmatrix}^T, \]

(8)

\[ \Phi_{\text{lctn}} = \begin{pmatrix} \phi_1^{\text{lctn}} & \cdots & \phi_i^{\text{lctn}} & \cdots & \phi_M^{\text{lctn}} \end{pmatrix}^T, \]

(9)

- distribution of the combat kit and on-board systems among the UAVs of the group and the established relative share of the combat kit, which can be spent on fire damage (suppression) of enemy air defense systems:
\[ \mathbf{S}^{\text{wpn}} = \mathbf{S}^{\text{wpn}} \times \Omega = \begin{pmatrix} n_{1,1}^{\text{wpn}} & \cdots & n_{1,K}^{\text{wpn}} \\ n_{2,1}^{\text{wpn}} & \cdots & n_{2,K}^{\text{wpn}} \\ \vdots & \ddots & \vdots \\ n_{M,1}^{\text{wpn}} & \cdots & n_{M,K}^{\text{wpn}} \end{pmatrix} \times \begin{pmatrix} \omega_1 \\ \vdots \\ \omega_K \end{pmatrix}, \] (10)

\[ \mathbf{S}^{\text{eqpm}} = \begin{pmatrix} \delta_{1,1}^{\text{eqpm}} & \cdots & \delta_{1,h}^{\text{eqpm}} & \cdots & \delta_{1,K}^{\text{eqpm}} \\ \delta_{2,1}^{\text{eqpm}} & \cdots & \delta_{2,h}^{\text{eqpm}} & \cdots & \delta_{2,K}^{\text{eqpm}} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ \delta_{M,1}^{\text{eqpm}} & \cdots & \delta_{M,h}^{\text{eqpm}} & \cdots & \delta_{M,K}^{\text{eqpm}} \end{pmatrix}, \] (11)

where \( \mathbf{S}^{\text{wpn}} \) is the matrix of the ammunition distribution for the UAV group;
\( \Omega \) is the vector of ammunition established rates consumption by types of weapons for tasks of enemy air defense breakthrough;
\( \mathbf{S}^{\text{wpn}} \) is the number of weapons by their types established for individual UAVs of the group that can be spent on the enemy air defense breakthrough;
\( \mathbf{S}^{\text{eqpm}} \) is the matrix of equipment distribution for UAVs of the group,
\( \delta_{i,k} \) is the sign of the type \( h \) equipment presence in the onboard complex of the \( i \)-th UAV;
\( K, H \) is the number of weapons types and equipment types, respectively;

- the number of effective fire impacts from the air defense systems on the UAV group during its flight along the established route:
\[ y^{\text{enemy}}(s) = (m_1(s) \cdots m_j(s) \cdots m_N(s))^T, \] (12)

\[ m_j(s) = \frac{\delta_j(s) \cdot n_j^{\text{chnnl}}}{\tau_j^{\text{cycle}}} \cdot v_{\text{gr}}(s) ds \cdot p_{1j}, \] (13)

where \( m_j(s) \) is the potential number of fire impacts on a group of UAVs from the \( j \)-th position of the enemy air defense system;
\( \delta_j(s) \) is the sign of the group hitting into the firing area of the air defense means located at the \( j \)-th position;
\( n_j^{\text{chnnl}} \) is the number of firing channels (targeting channels) of the air defense means located at the \( j \)-th position;
\( \tau_j^{\text{cycle}} \) is the firing cycle of the \( j \)-th the air defense means;
\( p_{1j} \) is the probability of UAV damage with a single impact from the \( j \)-th air defense means;

- expected losses of the UAV group from enemy air defense fire:
\[ M^{\text{losses}}(s) = 1 - \prod_{j=1}^{N} (1 - p_{1j})^{m_j(s)}, \] (14)

- predicted level of weakening of the impact of enemy air defense systems at: a given rate of ammunition consumption, the distribution of on-board systems among UAVs and the established battle order of the group:
\[ W^{\text{sprsn}}(s, \mathbf{S}^{\text{wpn}}, \mathbf{S}^{\text{eqpm}}, R^{\text{order}}, \Theta^{\text{fire}}, \Phi^{\text{fire}}, \Theta^{\text{lctn}}, \Phi^{\text{lctn}}, L^{\text{fire}}, L^{\text{lctn}}) = \{w_j\}, \] (15)

where \( w_j \) is the relative decrease of effective impacts number of air defense means located at the \( j \)-th position.

Indexes (1) - (11) characterize the application procedure of the UAV group. This index may be considered as control parameters (a desirable strategy). The decision maker manages the effectiveness of the group by changing these parameters. The effectiveness is measured by indexes (12) - (15).

The generated indicators characterize the state of the UAV group in relation to the processes of group control when solving the tasks of enemy air defense breakthrough. In a similar way, the
remaining lists of numerical indexes can be formed when other aspects of UAV group control from the table 1 are considering. The parametric space formed in this way will be relatively complete for the categorical pairs are considered. A control object can be represented as a system of metrics allows to quantitatively evaluate the actions performed, taking into account the received variety of aspects.

This result (multidimensionality) does not mean that a specific control under specific conditions should be based on a full set of state parameters. For a specific case, only those parameters that are inherent in the considered control aspect should be taken into account. However, the database of the designed ACS should contain a full variety of aspects or be built on a full-size control space, allowing for the adaptation of formalized control procedures to changing conditions and control tasks.

The next step in the conceptual design of the ACS is the step of defining formalized procedures for data transformation special software (SpS). Formalized SpS procedures that ensure the implementation of information relations and transformations between data groups are presented for the example of the studied aspect of control of a UAV group in relation to solving the problems of air defense breakthrough.

### 4. Determining of Data Transformation Procedures

It is convenient to determine SpS procedures on the basis of a conceptual scheme of information in the ACS of a group of UAVs (figure 1).

Since the categorical subset "C\W\G\D\A" considers the aspect of decision making for the application, or planning (programming) actions before operation, then here should define the procedures of two groups:
- forming a strategy (tactics) for using the UAV group, \( G \subseteq X^* \times S \times T \);
- forming theoretically attainable state parameters, \( U \times S \times T \rightarrow X^{\text{att}} \).

For the generated indexes (1) - (15), the procedures of the first group should include:
- determining of the route, profile, flight mode and combat order of the UAV group when the enemy's air defense breakthrough with fire strike and jamming, in case the parameters of the order of using the group are set. In a formalized form, the procedure is described as:

\[
\int_{s_0}^{s_{\text{end}}} \| \Psi_{\text{enemy}}(s) \| ds = \min ,
\]

\[
\psi^{\text{gr}}(s) \in V^{\text{perm}}(R, s), \quad R^{*}(s) \in R^{\text{perm}}, \quad R^{\text{order}}(s) \in R^{\text{order}}^{\text{perm}},
\]

\[
\theta^{\text{fire}} \in \Phi^{\text{fire}}^{\text{perm}}, \quad \phi^{\text{fire}} \in \Phi^{\text{fire}}^{\text{perm}}, \quad \theta^{\text{lctn}} \in \Phi^{\text{lctn}}^{\text{perm}}, \quad \phi^{\text{lctn}} \in \Phi^{\text{lctn}}^{\text{perm}},
\]

\[
L^{\text{fire}} = L^{\text{fire}}^{\text{given}}, \quad L^{\text{lctn}} = L^{\text{lctn}}^{\text{given}}, \quad E^{\text{wpn}} = E^{\text{wpn}}^{\text{given}}, \quad \Omega = \Omega^{\text{given}}, \quad E^{\text{epm}} = E^{\text{epm}}^{\text{given}}, \quad S^{\text{air dfnse}} = S^{\text{air dfnse}}^{\text{given}},
\]

where \( S^{\text{air dfnse}}^{\text{given}} \) is the specified data on the enemy air defense system (basis points, positions, types and number of weapons);

\( V^{\text{perm}}(R, s), R^{\text{perm}}, R^{\text{order}}^{\text{perm}}, \theta^{\text{fire}}^{\text{perm}}, \phi^{\text{fire}}^{\text{perm}}, \theta^{\text{lctn}}^{\text{perm}}, \phi^{\text{lctn}}^{\text{perm}} \) is the field of admissible values for the parameters of the routes, and the flight velocity profiles, battle formations UAV group;

\[ L^{\text{fire}}^{\text{given}}, L^{\text{lctn}}^{\text{given}}, E^{\text{wpn}}^{\text{given}}, \Omega^{\text{given}}, E^{\text{epm}}^{\text{given}} \) are the given parameters the application of the group.

The decision maker determines the route, profile, flight modes and battle formation (location relative to the reference point, the direction and width of the reconnaissance and jamming sectors with airborne means) of the UAV group, which ensure the minimum norm of the vector of effective actions of the enemy air defense when the UAV group passes route, for the established version of the
procedure for using a group of UAVs (distribution of combat kit and equipment for UAVs, the established rate of ammunition consumption for fire destruction of enemy air defense systems), with a given enemy air defense. That is, the flight of a group of UAVs is programmed as a whole, including maneuvering in height, direction, speed, rebuilding of UAVs, turning on (off) their onboard complexes.

Also, the value of expected losses can be used as a criterion for selecting a program

\[
\int_{s_0}^{s_{end}} M^{losses}(s) ds = \min,
\]

or the norm of the vector of the predicted level of weakening of the impact of enemy air defense system

\[
\int_{s_0}^{s_{end}} \| W^{spprsn}(s) \| ds = \max,
\]

- determining of the procedure for using a group of UAVs (distribution of combat formation and equipment for UAVs, the established rate of ammunition consumption for fire destroying of enemy air defense systems) with a specified route, profile, flight mode and combat formation of the group. In a formalized form, the procedure is presented as:

\[
\| \Omega \| = \min, \\
L^{fire}^* \in L^{fire}_{perm}, \quad L^{lctn}^* \in L^{lctn}_{perm}, \\
\mathbf{Z}^{wpn}^* \in \mathbf{Z}^{wpn}_{perm}, \quad \mathbf{Z}^{eqpm}^* \in \mathbf{Z}^{eqpm}_{perm}, \\
\mathbf{v}^{gr}(s) = \mathbf{v}^{gr*}(s), \quad R(s) = R^{order}(s), \quad R^{order}(s) = R^{order*}(s), \\
\mathbf{\theta}_{lctn} = \mathbf{\theta}_{lctn}^*, \quad \mathbf{\phi}_{lctn} = \mathbf{\phi}_{lctn}^*, \\
\mathbf{\theta}_{lctn} = \mathbf{\theta}_{lctn}^*, \quad \mathbf{\phi}_{lctn} = \mathbf{\phi}_{lctn}^*, \\
\mathbf{\xi}_{air dfnse} = \mathbf{\xi}_{air dfnse_{given}}.
\]

The decision maker determines the procedure for using a group of UAVs to bring air defense, which minimize the rate of a combat set consumption spent on fire suppression of air defense, for a given: flight mode and battle formation of the UAV group; formation of enemy air defense means;

- determining of the dependence of the characteristics of the effectiveness of mutual fire impact and electronic suppression of UAVs of a group and enemy air defense systems on the established route, profile, flight modes, combat order of the group, the procedure for its use, as well as the characteristics of the enemy air defense system:

\[
W^{spprsn} = W^{spprsn}(s, R, v^{gr}, R^{order}, \mathbf{Z}^{wpn}, \mathbf{Z}^{eqpm}, \mathbf{\theta}_{fire}^*, \mathbf{\phi}_{fire}^*, \mathbf{\theta}_{lctn}^*, \mathbf{\phi}_{lctn}^*, L^{fire}, L^{lctn}),
\]

\[
= M^{losses}(s, R, v^{gr}, R^{order}, \mathbf{Z}^{wpn}, \mathbf{Z}^{eqpm}, \mathbf{\theta}_{fire}^*, \mathbf{\phi}_{fire}^*, \mathbf{\theta}_{lctn}^*, \mathbf{\phi}_{lctn}^*, L^{fire}, L^{lctn}),
\]

\[
\mathbf{v}^{enemy} = (s, R, v^{gr}, R^{order}, \mathbf{Z}^{wpn}, \mathbf{Z}^{eqpm}, \mathbf{\theta}_{fire}^*, \mathbf{\phi}_{fire}^*, \mathbf{\theta}_{lctn}^*, \mathbf{\phi}_{lctn}^*, L^{fire}, L^{lctn}).
\]

The second group of procedures, namely the procedures for determining the theoretically achievable state parameters, includes:

- determining of the reach (maximum flight endurance) of the UAV group for the established flight modes;

- determining of the boundaries of the boundaries of the area of fire, jamming and reconnaissance for onboard means (systems, complexes) of UAVs;

- determining of the boundaries of areas: of fire by anti-aircraft missile units; of jamming of UAVs by electronic warfare units; of airspace reconnaissance by radio engineering units; of guidance and reach of enemy fighters for the established procedure for using a group of UAVs.
The STR procedures for the remaining categorical subsets are formed by analogy with the above example. These procedures form a complete set, on the basis of which poly-aspect procedures for the regulations of the designed ACS are created. Subsequently, sequential regulations are distributed among the control system devices. Devices can be both individual functionaries (operators) performing the work of the system and means of processing and converting information (for example, an on-board computer complex of a UAV). The result of this stage is the final formation of the concept of a promising ACS.

In practice, the design of ACS usually begins immediately with the stage of defining procedural regulations and their distribution between devices, bypassing the formation of the concept of information and the creation of a parametric control space. This approach is based on the postulate of using a prototype, which is the current management practice. In their absence, if a control system is created for a new object, analogs of existing control structures, similar in content, are considered as a prototype. However, in this case, the problem of completeness of information arises, on the basis of which a new APCS is designed. There are no guarantees that over time it will not be necessary to modify the software of the created ACS, since the previously not obvious, but turned out to be important in practical control aspects of control were not taken into account. Such an evolutionary process of development of previously created automated control systems is not always economically feasible and technologically achievable.

The proposed method for forming a parametric space based on categorical analysis does not in itself guarantee completeness. The generated metrics for assessing the state depend on the subjective choice of the set of categorical pairs used in the analysis. So, in this case, the aspect of interaction of the UAV group with the external infrastructure of information, navigation and combat support, of UAV group control with using the ground and air-based support group was outside the analysis. That is, it would be advisable to supplement the categorical subsets by applying to the analyzed integrity of such a categorical pair as: “Internal – External” (“I-E”). However, it would increase the already large list of aspects of the analysis (Table 1), which is impossible within the framework of one article. The purpose of the article is not a full-size design of the ACS concept, but a demonstration of the proposed method.

5. Conclusion
The article presents a methodology of conceptual design of ACS with using the example of ACS by a UAV group. The methodology includes the main stages of creating an ACS concept: the formation of a parametric control space based on a constructive scheme of data groups and information interaction procedures. The problem of providing the completeness of information is revealed and the method of its solution based on the method of categorical analysis is presented.

Methodical analysis allows to put in order the reasoning of the ACS creator. At the same time, taking into account the main gnoseological features of analysis (elimination of the contradictions of the integrity opposites), ensures the completeness of the analysis, regardless of the subjective thinking of the designer.

When solving the problem of ensuring the completeness of the information used in the designed ACS, subjectivity is transferred from the level of determining the metrics of the parametric control space, which has a large dimension and is difficult to subjectively perceive as a single integrity, at the level of choosing categorical pairs that set the opposites of the process which are researched. The perception of integrity as a system of categorical subsets is simpler because its image have smaller size.

The article shows an example of forming the conditions of the state of an UAV group in relation to the breakthrough of enemy air defense means with the use tactics of fire strike and jamming. The proposed list of numerical metrics contains parameters that determine route, profile, flight mode, battle formation, the order of using the UAV group, and the achieved efficiency.

Control procedures are proposed for the formed parametric space, including the formation of a strategy (tactics) for the use of the group and the creation of theoretically achievable state parameters.
The results presented in the article are expedient to use for the conceptual analysis and design of promising automated control systems in the absence of a structured formulation of design problems. The use of the categorical analysis method allows significantly reduce the period of delineating the required areas of research and reaching the forefront of problems in these areas, due to the use of a deductive approach instead of an inductive one.

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