1. Introduction

Present concepts of development and special-purpose usage of operational and tactical unmanned aerial vehicles (UAVs) assume that in the proximal 15–20 years they will perform operational tasks as a part of the mixed groups of piloted aerial vehicles (PAVs) and UAVs of various tactical designations [1].

It is considered that the joint application of PAVs and UAVs will expand piloted aviation capabilities, bring new elements to aircrafts battle application technologies, increase the efficiency, reduce battle losses of flight personnel and expenses for operations conducting by these aerial vehicles.

Simulation modeling is the basic tool for an aircraft conceptualization at the present time. The necessity of PAVs and UAVs model analysis requires the development of appropriate simulation complexes of standard operations provided by these aerial vehicles.

In the capacity of standard operations the following are considered:

- the defeat operation of an aircraft-carrier naval group (ACNG) in following variants of formation—multipurpose aircraft-carrier group and aircraft-carrier battle group. The task of its defeat is one of the main aviation missions on a marine (ocean) combat theatre (CT) [2];

- the defeat operation of ground-based targets by the joint use of aviation and naval- or surface-based winged missiles (WM) in active jamming and firing counteraction environment [3];

- the defeat operation of the Early Warning and Control Systems (EWACS) airplane as the basic element of the network-centric operations in the conditions of its reliable battle cover provided by specially appointed air forces [4].
Each of considered complexes represents the integrated simulation environment and contains two components:

- the automated system to create the rational combat scenario at the conditions of the active counteraction, ensuring demanded damage level to the enemy and own losses not above the admissible level;
- the modeling system to simulate an active operation in compliance with the planned scenario variant and an efficiency estimation of the warring parties actions.

In modeling complexes for each of the opposing sides the common informational and control field models, providing for combat actions in the common informational and control space are implemented [5]. So, in particular, the availability of the common informational and control field allows to implement the UAVs group application and the air targets over-horizon zone of damage by long-range and medium-range surface-to-air complexes.

The PAVs and UAVs control mode selection in modeling complexes was carried out depending on a tactical group designation, its mission, the operational flight stage, the current warfare setting, the available information, presence of demanded information interchange channels, the level of UAV’s self-regulation and intellectuality. Modeling complexes implement the following modes to control groups of UAVs [6]: centralized control, leader-control (hierarchical) and decentralized control (“network” or “gregarious” control).

In control modes implementing algorithms [7] the PAVs and UAVs control vector includes attack, slip and velocity bank angles, engine and air brakes control variables. The given vector is formed as a function of the difference between required and current values of adjustable parameters which determine the selected guidance method, the maneuver, desired flight path, given intervals and distances between groups and within a group. At the same time, occasions of collision, mutual eliminations are excluded and conditions of the sustained informational exchange between UAVs and PAVs are ensured.

The simulation results estimations of mentioned operations have been carried out by the single-aspect “cost-efficiency” criteria [2–4].

2. The simulation modeling complex of PAVs and UAVs joint actions in the aircraft-carrier naval group defeat operation

In the developed modeling complex [2] the ACNG defeat operation is conducted by ground-based aviation formations including the following mixed PAVs and UAVs groups of various tactical purpose: strike, electronic counter-measures (ECCM), fighter escort, demonstrative, reconnaissance and target acquisition, EWACS damage groups.

The automated planning system includes the following mathematical models (MM):

- MM₁—to generate alternative pathways variants for PAVs and UAVs groups of various tactical purposes;
- MM₂—to assign information-management systems interacting with PAVs and UAVs groups, the number and types of information-management channels, arranging the common and local informational and control fields for aviation tactical groups at each stage of their operational flight, the composition and values of given fields parameters;
- MM₃—to control of UAVs groups;
- MM₄—to determine pathways and flight profiles efficient by the survival rate criterion and realizable by fuel exception;
- MM₅—to determine the demanded battle allocations of strike and supporting groups of PAVs and UAVs;
- MM₆—to assign patrol zones, pathways and flight profiles to attain these zones of ECM groups, EWACS airplane and interceptors providing the escort of the allocated zones;
• MM7—to determine battle formations of joint aviation groups of various tactical designation at their pathways with constraints on their sustained informational exchange conditions;
• MM8—to obtain the space-time coordination of piloted and unmanned air forces and facilities combat actions according to hierarchic level of UAVs groups control at all stages of their operational flight;
• MM9—to select an efficient combat scenario from the set of alternative variants by the given optimality criterion.

The simulation system includes the following mathematical models:

1) MM of operational flight process of joint aviation groups and groups of various tactical purposes which perform the main and supporting tasks in compliance with the created scenario of ACNG defeat. The given model includes MM of operational flight fragments;
2) MM of ACNG air defense system forces and facilities activity at air raid repulse including MM of operational fragments;
3) MM of the warring parties damage levels estimation.

According to simulation results the following control modes for various groups are selected:
• for ECM-groups: centralized control—combat actions in a target area, hierarchical control—path following flight;
• for strike groups: hierarchical control—path following flight, “network” control—combat actions in a target area;
• for reconnaissance and fighter escort groups: hierarchical control at all flight stages;
• for demonstrative groups: similar to control modes for strike groups.

![Figure 1](image.png)

**Figure 1.** A modeling fragment of the ACNG defeat operation scenario in the “distance–altitude” plane projection.

On the figure 1 a modeling fragment of the ACNG defeat operation scenario in the “distance–altitude” plane projection at the simulated time $T = 4350$ sec (flight paths of the anti-ship and air-defense surface-to-air missiles are shown) is presented.

3. The simulation modeling complex of PAVs, UAVs and winged missiles joint actions in a ground-based objects defeat operation

Ground-based strike objects, the strike time “$X$”, relief and underlying surface types and meteorological conditions are given at CT in an operational direction coordinate system [3].
The computational operational task consists in:

- attack the allocated ground-based objects by WM, PAVs and UAVs groups at the defined time moment related to the strike time "X";
- attack an area air defence system, which constitutes a threat to aviation tactical groups and WM groups at their trajectories, by groups of PAVs and UAVs at the time moment determined from the strike time "X";
- attack a local air defence systems at the time moment determined from the strike time "X";
- defeat a loitering EWACS aircraft of the area air defence system at the time moment determined from the strike time "X".

The automated planning system includes the following mathematical models:

- MM$_1$—to select a detachment, pathways and altitude-airspeed flight profiles efficient by the minimum of battle detachment criterion for each object of strike;
- MM$_2$—to determine an efficient supporting groups membership;
- MM$_3$—to form an efficient pathways, altitude-airspeed flight profiles and battle formations parameters for supporting groups with allowance for informational-network conditions constraints and control mode limitations;
- MM$_4$—to select the essential elements of strike objects and determine defeat combinations resulting in an object elimination by the given type, aiming points positions and target approach parameters for the selected variant of WM guidance system; to plan the ground-based objects attacks by WM including estimated lossless and battle detachments of WM, pathways and flight profiles selection, WM-groups trajectory appointment; to define formations and start times of WM, space-time schedules of WM-carriers take-off;
- MM$_5$—to plan an area air defence system objects attack including strike groups and supporting groups membership selection and to determine space-time schedules of their take-off;
- MM$_6$—to define patrol zones of the EWACS airplane, providing for informational and control space of air groups, and its flight path to the zones;
- MM$_7$—to plan the EWACS airplane of an area air defence system defeat operation;
- MM$_8$—to perform the space-time coordination of each air tactical group, determine take-off times for each WM carriers group, air tactical groups and WM start times;
- MM$_9$—to determine disposable quantity and types of informational channels, organizing network-centric informational and control fields for air tactical groups on each stage of their combat flight according to a selected operation scenario.

The simulation system includes the following mathematical models.

- MM of operational flight process of joint aviation groups and groups of various tactical purposes which perform (in compliance with the created scenario) the main and supporting tasks of ground-based objects defeat operation. The given model includes MM of operational flight fragments.

A standard combat flight consists of the following sequentially carried out stages:

1) take-off, battle order setup;
2) flight to a mission accomplishment region;
3) target approach (toward the given region or to the firing line);
4) activity in the mission accomplishment region;
5) flight from a mission accomplishment region;
6) disbandment and landing.
To control PAVs and UAVs groups the following modes are selected:

1) for PAVs and UAVs ECM-groups: centralized control—at flight stage 4 and hierarchical control—at stages 1–3, 5–6;
2) for PAVs and UAVs strike groups: hierarchical control—at flight stages 1–3, 5–6 and decentralized (“network”) control—at flight stage 4;
3) for PAVs and UAVs reconnaissance and fighter escort groups: hierarchical control at all flight stages.

- MM of an aerial and local air defence systems forces and facilities, man-portable air defence systems, placed on CT, activity during the aviation and WM-groups raid repulse, including MM of operational fragments.
- MM of the warring parties damage levels estimation.

**Figure 2.** A modeling fragment of PAVs, UAVs and winged missiles joint actions in the ground-based objects defeat operation in projection onto the $X_gOY_g$ plane of the Earth coordinate system.

On the figure 2 a modeling fragment of PAVs, UAVs and winged missiles joint actions in the ground-based objects defeat operation in projection onto the $X_gOY_g$ plane of the Earth coordinate system is depicted.

4. The simulation modeling complex of PAVs and UAVs joint actions in the EWACS airplane defeat operation

The defeat operation of the EWACS airplane, loitering at a constant altitude by “box-pattern” or “eight-pattern” flight route is considered [4].

Inside the above mentioned zone there are interceptors, patrolling by “box-pattern” trajectory from the “air alert” position and protecting the EWACS airplane from the airborne threats (AT).

In case of need the EWACS airplane involves subsidiary interceptors from the “ground alert” position for threatening AT intercept.

Fighters, ensuring the protection of EWACS airplanes from AT are armed by long-range or medium-range missiles of the “air-to-air” class.

For the purpose of radio jamming against AT-threats and countermeasure covering of escort fighters the EWACS airplane can implicate ECM-aircrafts, patrolling at the given distances.
The defeat EWACS airplane operation is performed by an aviation formation including piloted and unmanned aerial vehicles and ECM-planes.

The formation belonging fighters groups fulfill the coordinated attack of escorting the EWACS airplane interceptors from various directions and altitudes with the assistance of ECM-planes which protect them by radio jamming during a flight in joint battle formations or from air patrol zones.

The simulation model of the discussed mission includes the following mathematical models:

- MM of aviation groups flight at allocated pathways and altitude-airspeed flight profiles.
- MM of target distribution and guidance of attacking the EWACS airplane interceptors groups. The model implements two target distribution algorithms which differs by the striking air unit “A” (which actions must be supported by other air units) defining method:
  1) algorithm of target distribution with the one-time strike unit “A” allocation;
  2) algorithm of target distribution with the dynamic allocations of the strike unit “A”.

As guidance algorithms of fighters allocated on the EWACS airplane, depending of the available information can be used the following [7]:

- the “attack with the altitude-changing” method;
- the “pursuit with the altitude-changing” method;
- a flight by the given route points and altitude-airspeed flight profile;
- the long-range air combat with battle outposts of interceptors defending the EWACS airplane. The following methods can be used as missiles guidance algorithms [4]: at the inertial corrected route path—“proportional guidance”, “coincidence method (‘three-base” method)”, “arching trajectory with proportional guidance in the horizontal plane”, “arching trajectory with coincidence method in the horizontal plane”, “arching trajectory with proportional “pincers” (“outflanking”) maneuver in the horizontal plane” (used two immediately launched missiles) methods; at the self-guidance route part—“proportional guidance” method only;
- ECM-planes actions at their flight inside combat formations and from the air loitering zones;
- the attack of the EWACS airplane.

![Figure 3. A modeling fragment of the EWACS airplane defeat operation scenario in the “distance–altitude” plane projection.](image-url)
A modeling fragment of the EWACS airplane defeat operation scenario in the “distance–altitude” plane projection is depicted at the figure 3. This fragment presents the simulated time $T = 790$ sec—the moment of missile’s hit into the EWACS airplane, trajectories of fighters and air-to-air missiles.

5. Conclusion
Complexes of mathematical models of planning, simulation and efficiency estimation of piloted and unmanned aviation joint actions in operations against naval, ground-based and flying objects are presented.

The developed simulation modeling complexes can be used as a part of a toolkit to conduct researches for PAVs and UAVs conceptual characteristics and their onboard knoware substantiation, tactics selection and efficiency estimation of their application.

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