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THE CONCEPT OF INTEGRATING UNMANNED AIRCRAFT INTO A SINGLE AIRSPACE WITH MANNED AIRCRAFT

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Abstract

Remotely piloted aviation systems are a new component of the aviation system, which, based on the latest developments in the field of aerospace technologies, open up new and expand existing opportunities for civil/commercial applications, increase the level of flight safety and efficiency of all civil aviation. The safe integration of remotely piloted aviation systems into non-segregated airspace is a lengthy process that requires coordinated action by many stakeholders, each of whom brings their own expertise to the process. Until now, the activities of civil aviation have been based on the concept that a pilot controls an aircraft while on board, and most often with passengers. Flying aircraft without a pilot on board raises a number of important technical and operational issues that are currently being actively studied by the aviation community. The most important task is to ensure that the integration of remotely piloted aircraft into non-segregated airspace and their use at airfields in no way leads to an increased risk to the safety of aircraft with a pilot on board. The paper considers decision-making models for the management of manned and unmanned aircraft in a single airspace, which provides a detailed analysis of the features of human-operator interaction, automated control systems and intelligent algorithms for remotely piloted aircraft systems, limitations caused by flight safety requirements in accordance with ICAO standards and recommended practices, regulatory and legal regulation and high dynamics of air the surroundings. Special attention is paid to methods of situational awareness, conflict forecasting, responsibility allocation between the pilot and automation, as well as adaptive and hybrid decision-making models based on control theory, probabilistic methods and elements of artificial intelligence. The results of the research can be used in the development of promising air traffic control systems and onboard intelligent systems, the development and updating of new flight rules that ensure the safe and effective integration of manned and unmanned aircraft into a single airspace.

Keywords

unmanned aircraft, unified airspace, integration of unmanned aircraft, U-space, air traffic control, urban air mobility, digital ecosystem

1. Introduction

Over the past decade, unmanned aircraft have become a key element in the development of global aviation activities, the use of which has found its relevance in geodesy, logistics, agriculture, energy, nature conservation, medicine and emergency situations. During this time, there has been a tremendous increase in the use of unmanned aircraft system (UAS), both small and large UAS capable of flying hundreds of kilometers, and in 5-10 years it is expected that the commercial use of UAS will exceed the number of commercial flights of small aircraft.

The widespread use of UAS is due to a significant reduction in the cost of technology and the development of autonomous control; high demand for the rapid delivery of various household goods (mail and small cargo delivery, medicines); monitoring of power lines, pipelines and railways; application in the national economy (spraying fields, monitoring forest fires, floods, aerial photography), which requires regular and long-range flights, including beyond the line of sight of the operator of UAS [ICAO 2016].

However, separate airspace is currently being used, where manned aircraft system (MAS) and UAS are controlled separately, which does not fully meet current trends in the development of unmanned aviation and is due to limited airspace use (bans on flights in cities, reservation of airspace zones, insufficient digital management tools) and significantly hinders market development [ICAO 2020, EUROCONTROL 2020]. This circumstance necessitates the transition to an integrated system for the use of airspace, in which UAS perform flights on a common basis with manned aircraft, while ensuring the level of flight safety at all stages, from takeoff to landing.

The integrated airspace management system will create the most favorable conditions for mass commercial services, which will be driven by an increase in the number of operators and manufacturers of UAS and, as a result, the creation of new jobs, which will lead to an influx of large investments into the state. In turn, the relevant government agencies will be able to more quickly and effectively carry out ecosystem monitoring, border protection, fire intelligence, mapping, and emergency support. Commercial organizations and business structures will receive new business developments, which will make it possible to fly without significant restrictions, with uniform standards and regulation of this area of aviation activity [FAA 20204, SASAR 2021].

The modern development of technology, the emergence of UTM/U-Space, the development of collision avoidance systems and next-generation communications provide the foundation for the development of future aviation, in which UAS and MAS will be able to fly together and safely. All these functions are significantly cheaper when using a UAS, but they are impossible without access to large amounts of airspace. Ensuring flight safety is a key aspect of integration, since MAS and UAS already intersect in areas of airports and airfields, at low altitudes in cities and suburban areas, on patrol routes, etc., without common rules, this creates significant risks for all users of airspace, urban infrastructure and third parties [FAA/NASA 2018-2022].

Most of the regulations, especially regarding small UAS, beyond visual line of sight (BVLOS), mass operations and unmanned traffic management (UTM), have not yet been included in formal standards and recommended procedures (SARPs). In practice, States are forced to develop their own rules, which leads to a lack of synchronization of standards, lack of uniformity, and difficulties in international operations. The regulatory framework is not yet fully consistent with the pace of development of unmanned technologies. The main gaps — technical detail, cybersecurity, regulation of massive small UAS and UTM, as well as differences in national implementation — remain a serious obstacle to the full integration of UAS into the airspace. Further harmonization of standards, strengthening of technical requirements and expansion of international cooperation are needed to accelerate the development of the sector [ICA02018-EASA 2019].

Problem description. The development and research of decision-making models for the joint management of MAS and UAS will make it possible to form scientifically sound methods for improving the efficiency and safety of their operation, as well as create the basis for the subsequent implementation of intelligent and adaptive control algorithms in promising aviation complexes, which should formalize the choice of control actions, optimize the allocation of tasks and resources, and coordinate actions in real time, taking into account constraints and risks. When developing decision-making models, it is proposed to use the following methods [RTCA 2020-11- Kuchar J. K., Yang L. C. A 2000].

- system analysis and management theory of complex hierarchical systems with critical infrastructure;
- decision theory, probabilistic methods, and theory of random processes;
- methods of modeling processes in conditions of uncertainty;
- simulation modeling;
- methods of artificial intelligence and intelligent systems;
- analysis of the influence of the human factor on management processes.
- The object of the research is the processes of joint management of MAS and UAS in a single air and information space, which involve the development:
- formalized approach to modeling decision-making processes in the joint management of MAS and UAS taking into account the interaction of a human operator and automated controls;
- decision-making models that integrate levels of strategic, tactical, and operational management in an uncertain and dynamically changing environment;
- methods of coordination and assignment of tasks between MAS and UAS based on criteria of efficiency, safety and resource constraints;
- to formalize the influence of the human factor on the decision-making process in the joint management of aviation systems;

The proposed system has a multi-level structure and includes the following main components [FAA2020, Endsley M. R. 2017, Prescott T. 2024].

1.1. The level of data collection and merging

At this level, information is collected from various sources, including radar facilities, ADS-B systems, airborne UAS telemetry, navigation systems, and meteorological sources. To increase the reliability of information, data fusion is used to form a holistic view of the current air situation.

1.2. Air situation analysis leve

The data obtained is used to evaluate the current parameters of aircraft movement and predict their trajectories in a temporal and spatial context. Predictive models are used to identify potential conflict situations, including violations of minimum separation intervals.

1.3. Decision-making level

The decision-making level implements the formation of recommendations and control actions using rules, optimization methods and intelligent algorithms. Solutions may include changing the route, altitude, or flight speed, as well as reallocating priorities between aircraft. Depending on the level of automation, solutions can be transferred to the dispatcher, pilot, or UAS operator, or applied automatically.

1.4. The level of interaction

This level provides human-machine interaction and information exchange between the system, dispatching personnel and UAS operators. The interfaces are designed taking into account ergonomic requirements and the peculiarities of information perception in conditions of high dynamics of the air situation.

1.5. Features of joint management

Joint management of MAS and UAS is characterized by differences in the levels of autonomy and human responsibility for decision-making. In critical situations, priority is usually reserved for MAS, which should be taken into account when forming control actions. Additional restrictions are imposed by the requirements of certification and regulatory regulation [EASA 2019, Cook A., Tanner G. 2016, Kuchar J. K., Yang L. C. 2000].

1.6. *Introductions of integrated decision-making system for joint management of MAS and UAS.*

The system is a complex of mathematical models and algorithms that ensure the safe and effective interaction of MAS and UAS in a single airspace.

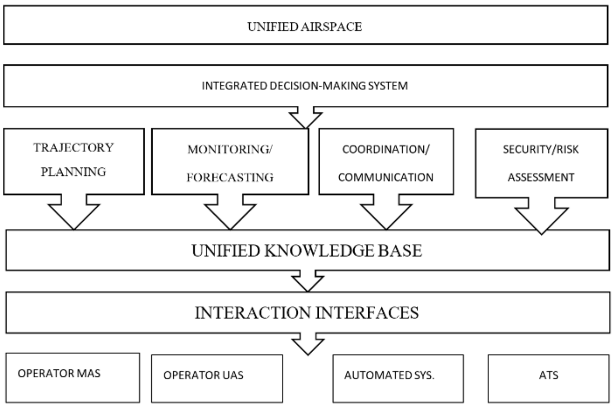


Figure 1. General scheme of Integrated decision-making system for joint management of MAS and UAS.

2. Dynamic air space distribution model.

This model is a functional component of an integrated air traffic control system (ATS) designed to coordinate the use of airspace while simultaneously performing ATS and UAS flights.

The module interacts with classic ATS systems, as well as with UTM systems that provide traffic management for UAS. At the same time, coordination of decisions made by the dispatcher and automated control algorithms is ensured [Bishop C. M. 2006 - Pinto Neto E. C., Baum D. M., Almeida Jr. J. R., Camargo Jr. J. B., Cugnasca P. S. 2022]

The main functions of the dynamic airspace module are:

- formation and modification of space-time zones of airspace in a four-dimensional representation;
- dynamic allocation of corridors and time zones for UAV flights;
- forecasting the trajectories of the MAS and UAS;
- automated detection of potential conflict situations;
- development of recommendations or management actions for their resolution;
- adaptation of the airspace structure to changes in the meteorological and aeronautical situation.

The module supports various levels of UAS control autonomy, from operator control to fully automatic modes.

The input data for the information support module's operation are flight plans for MAS and UAS, surveillance and positioning data, telemetry information, meteorological data, as well as information on time and regulatory restrictions on the use of airspace.

The module results in permits and restrictions on the use of airspace, adjusted flight paths, notifications of conflict situations, and recommendations for air traffic controllers and operators [Kuru K., Pinder J. M., Watkinson B. J., et al. 2023- Kuchar J. K., Yang L. C. 2000].

Dynamic airspace is considered as a four-dimensional area:

$\boldsymbol{\Omega} \subset \boldsymbol{R}^3 \times \boldsymbol{R},$ MAS and UAS $i \in 1, \dots N$, described by the state vector

$$\boldsymbol{X_i}(\mathbf{t}) = \begin{bmatrix} \boldsymbol{p_i(t)} \\ \boldsymbol{v_i(t)} \\ \boldsymbol{q_i(t)} \end{bmatrix}, \qquad \textbf{(1)}$$

Where

$\boldsymbol{p_i(t)} \in \boldsymbol{R}^3$- position vector,

$\boldsymbol{v_i(t)} \in \boldsymbol{R}^3$- velocity vector,

$\boldsymbol{q_i(t)}$ **–** parameters of flight modes.

The dynamics of motion is described by the equation:

$$\boldsymbol{p_i(t) = v_i(t), v_i(t) = u_i(t)} \qquad \textbf{(2)}$$

The spatial and temporal zones of the unified airspace are represented as:

$\Omega(\boldsymbol{t}) = \boldsymbol{U_{k=1}^{M} Z_k(t), Z_k(t) = \langle S_k(t), T_k, r_k \rangle,}$ where:

$\boldsymbol{T_k}$ **–** time interval,

$\boldsymbol{r_k}$- priority of flights (UAS or MAS).

The task of the module is to select management decisions and configuration of flight zones in which there is no conflict for all pairs *i* and *j*. The occurrence of a conflict is possible under the condition:

$\exists_t \in \boldsymbol{[t_0, t_0 + T_p]}: \boldsymbol{\|p_i(t) - p_j(t)\| < D_{min}}$ **,** where $\boldsymbol{T_p}$ - the forecasting horizon.

Optimization of the use of a single airspace is carried out according to multi-criteria functionality:

$\boldsymbol{J = a_1 J_{safe} + a_2 J_{cap} + a_3 J_{eff},}$

$\boldsymbol{J_{safe}}$- safety indicator,

$\boldsymbol{J_{cap}}$- throughput capacity,

$\boldsymbol{J_{eff}}$ **–** trajectory efficiency,

$\boldsymbol{a_k}$- weight coefficients.

The operation of the model includes the following stages showed in Figures 2-3.

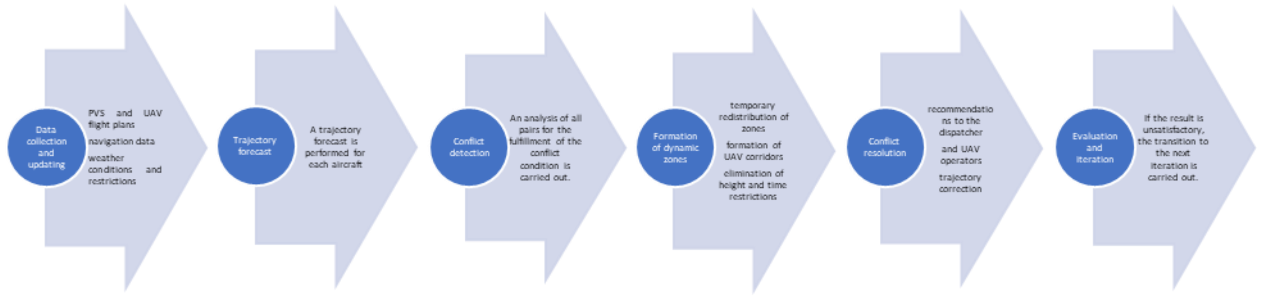


Figure 2. Stages of the model's operation (1)

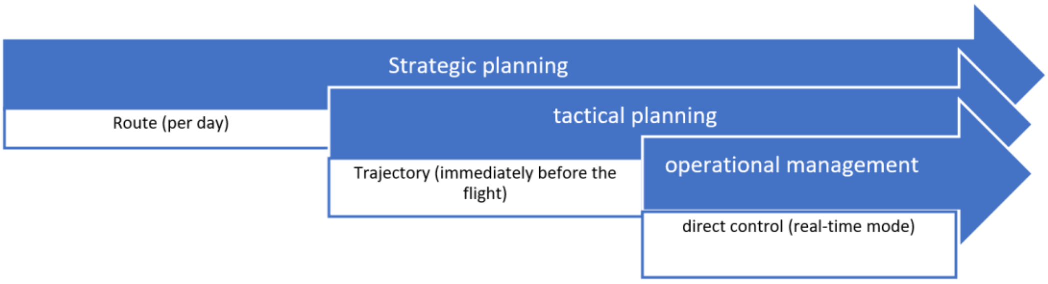


Figure 3. Stages of the model's operation (2)

3. Strategic planning

Strategic planning (Pre-flight) is the coordination of flight plans (including 4D trajectories: 3D+time) between all participants and ATC/UTM services.

The air space model. Lots of aircraft:

$$A = A^M \cup A^U, A^M \qquad (3)$$

controlled by ATS, A^U- controlled by U-space serves providers.

The airspace is described by the following expression:

$$Z = Z^{ATM} \cup Z^U,$$

where Z^{ATM}- controlled airspace,

Z^U- U- space airspace volumes,

$X_z\ (t)$- Dynamic airspace reconfigurations.

By U-space services described of UAS parameters:

$$\alpha \in \mathrm{A}^U \rightarrow ID_\alpha, class_\alpha$$

They are used in separation coefficients and probability constraints.

Flight plan of UAS: $\gamma_\alpha \rightarrow UAS\ flight\ plan,$ under restrictions $\gamma_\alpha \in \{Z|X_z(t) = 1\}$ corresponds to the validation of trajectories. Conflict situation $\mathrm{C}_{\alpha\beta}(z, h, t)$ according services of Strategic conflict Detection and capacity management, under probabilistic constraints $P(C_{\alpha\beta} = 0) \geq 1 - \varepsilon$, optimization $minJ(\gamma_\alpha)$.

ATM Flight Plan 4D trajectory Piloted aircraft $\gamma_\alpha^{ATM} = \{(x, y, h, t)\}_1$, agreement of $\gamma_\alpha^{ATM} \cap \gamma_\beta^U = \emptyset_1$, bandwidth limitations: $\Sigma_{\alpha\epsilon A} I(z, h, t) \geq C_{zb}$, where C_{zb}- declared capacity of sector.

The module operates in discrete time and includes the following steps:

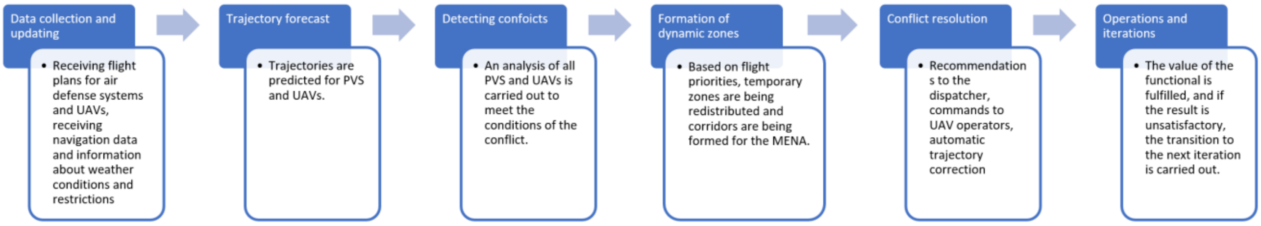


Figure 4. Steps of module operates in discrete time

Tactical planning. Tactical trajectory planning is a level of flight planning focused on the short and medium term (seconds—minutes), the purpose of which is to ensure safe separation of MAS and UAS; adapting trajectories to a dynamically changing environment; performing missions while respecting airspace restrictions and human-machine interaction. Unlike strategic planning (route, trains, schedules), the tactical level works with real time and uncertainties [Austin R. 2010, Valavanis K. P., Vachtsevanos G. J. 2015].

The joint operation of MAS and UAS is characterized by:

- **Asymmetry of management** - the MAS is controlled by a person with high cognitive flexibility; the UAS is an automated system with formalized algorithms.
- **Differences in flight performance** are determined by different restrictions on maneuverability, speed, overloads, as well as different requirements for safe distances.
- **The heterogeneity of the levels of autonomy** UAS appears to be remotely controlled; semi-autonomous; fully autonomous.

The tactical planning model should forecast the movement of UAS and UAS over a limited planning horizon; detect and prevent conflicts (collision avoidance); reschedule trajectories in case of changing weather conditions and failures; coordinate solutions between MAS automation and the actions of the UAS pilot; minimize the load on the pilot and ATS operators [Wooldridge M. 2009, Balas A. V. 2016].

When considering the set of aircraft described in (3), where each aircraft state is determined by the vector described in (2), the dynamics of aircraft movement is described:

$X_i\ (\boldsymbol{t}) = \boldsymbol{f_i}(X_i\ (\boldsymbol{t}), \boldsymbol{u_i}(\boldsymbol{t}), \boldsymbol{w_i}(\boldsymbol{t}),$ **(4)**

where $\boldsymbol{u_i}(\boldsymbol{t})$- controlling influence, $\boldsymbol{w_i}(\boldsymbol{t})$- weather conditions, measurement errors.

Tactical planning is carried out on the final horizon: $\boldsymbol{t} \in [\boldsymbol{t_0}, \boldsymbol{t_0} + \boldsymbol{T}]$ at the trajectory of aircraft $\boldsymbol{\tau_i} = \{\boldsymbol{x_i}(\boldsymbol{t})\}_{\boldsymbol{t}=\boldsymbol{t_0}}^{\boldsymbol{t_0}+\boldsymbol{T}}$, and dynamic restrictions on speed, overload, roll and pitch angles, where for any,

$\boldsymbol{i}, \boldsymbol{j} \in \boldsymbol{A}, ; \boldsymbol{i} \neq \boldsymbol{j};\ \left\|\boldsymbol{p_i}(\boldsymbol{t}) - \boldsymbol{p_j}(\boldsymbol{t})\right\| \geq \boldsymbol{d_{min}}, \forall(\boldsymbol{t}) \in \left[\boldsymbol{t_{0,}} \boldsymbol{t_0} + \boldsymbol{T}\right]$
(5)

Where the airspace restriction is described $\boldsymbol{p_j}(\boldsymbol{t}) \in \boldsymbol{\Theta_k}, \forall \boldsymbol{k}$

Accounting for the human factor fleet for MAS is described by a model of deviation from the recommendations $\boldsymbol{u_t^M}(\boldsymbol{t}) = \boldsymbol{u_i^{rec}} + \boldsymbol{\beta_i}(\boldsymbol{t})$, $\boldsymbol{u_i^{rec}}$ - recommended management, $\boldsymbol{\beta_i}(\boldsymbol{t})$ - a random variable simulating the flight response, with a distribution $\boldsymbol{\beta_i} \sim \boldsymbol{N}(\boldsymbol{0}, \boldsymbol{\Sigma_i})$

For UAS, the task can be solved through game theory with conflicting interests, which results in receiving recommendations for the UAS in the control system, and for the pilot of the UAS in the form of recommendations.

Level 3: Operational control and safety is the process of forming and adjusting flight paths in real or quasi-real time, taking into account: airspace restrictions; weather conditions; aircraft characteristics; control room commands; unpredictable behaviour of other traffic participants.

Automated planning algorithms based on optimization methods, graph theory, Model Predictive Control methods, artificial intelligence [ICAO 2019, EUROCONTROL 2020].

The key problem of joint management is the difference in: the level of autonomy; reaction time; control and communication channels; responsibility for decision-making. MAS rely on a human pilot, while UAS operate on the basis of on-board algorithms, which requires consistent interaction protocols and uniform "detect and avoid" standards.

The safety of trajectory planning models is assessed by guaranteed conflict and collision prevention; resistance to sensor and communication errors; correct operation in case of incomplete or unreliable information; predictability of UAS behaviour for pilots and controllers. Probabilistic risk models; methods of reachability analysis; formal methods of verification and logical proof of properties; scenario modelling and digital twins are used for formal verification of security [7,8].

The model of the dynamics of the armed forces described in expressions (2), (3), and the conflict model (4) defines the task of optimal operational planning with constraints:

$$\boldsymbol{min_u J_i} = \int_{\boldsymbol{t_0}}^{\boldsymbol{t_i}+\boldsymbol{T}} \left(\left\|\boldsymbol{p_i}(\boldsymbol{t}) - \boldsymbol{p_i^{ref}}(\boldsymbol{t})\right\| \boldsymbol{1}^2 + \boldsymbol{\lambda}\|\boldsymbol{u_i}(\boldsymbol{t})\|\boldsymbol{1}^2\right) \boldsymbol{dt}$$

And under the conditions:

$$\begin{cases} x_i = f_i(x_i, u_i) \\ x_i(t_0) = x_i^0 \end{cases}, \begin{cases} x_i(t) \notin C_{ij}, \forall_j \neq i) \\ u_i(t_1) \in U_i \end{cases}$$

The condition of other aircraft is known with an error $\boldsymbol{x_j} = \boldsymbol{x_j} + \boldsymbol{\varepsilon_j}, \boldsymbol{\varepsilon_j} \sim \boldsymbol{N}(\boldsymbol{0}, \boldsymbol{\Sigma_j})$, $\boldsymbol{P}(\boldsymbol{d_{ij}}(\boldsymbol{t})\ \geq_1 \boldsymbol{d_{min}}) \geq \boldsymbol{1} - \boldsymbol{\delta}$, this allows you to take into account ADS-B errors, communication delays, and the human factor.

Based on the above, we will draw up a general flowchart for safe trajectory planning, where the current state is at the input. $x_i(t)$, forecasts of MAS $x_i(t\!:t+T)$ and the limitations of airspace. Safety is ensured by the invariance and the formal reachability constraint, showed in figure 5.

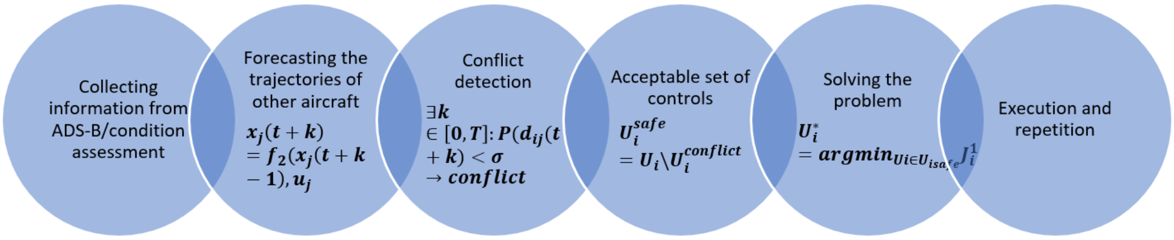


Figure 5. The flowchart for safe trajectory planning

The monitoring and forecasting model is designed for continuous monitoring of the air situation, forecasting is carried out based on the analysis of time series of flight parameters and risk factors using probabilistic and intelligent methods, which makes it possible to assess trends in the state of the system and the likelihood of dangerous situations over a given time horizon.

The results of monitoring and forecasting are used in the decision-making system to generate warnings and corrective control actions that improve flight safety in an uncertain and dynamically changing environment. The model consists of five interconnected levels shown in the figure 6. [ICAO 2019, EASA 2019, Cook A., Tanner G. 2016, Kuchar J. K., Yang L. C. 200]

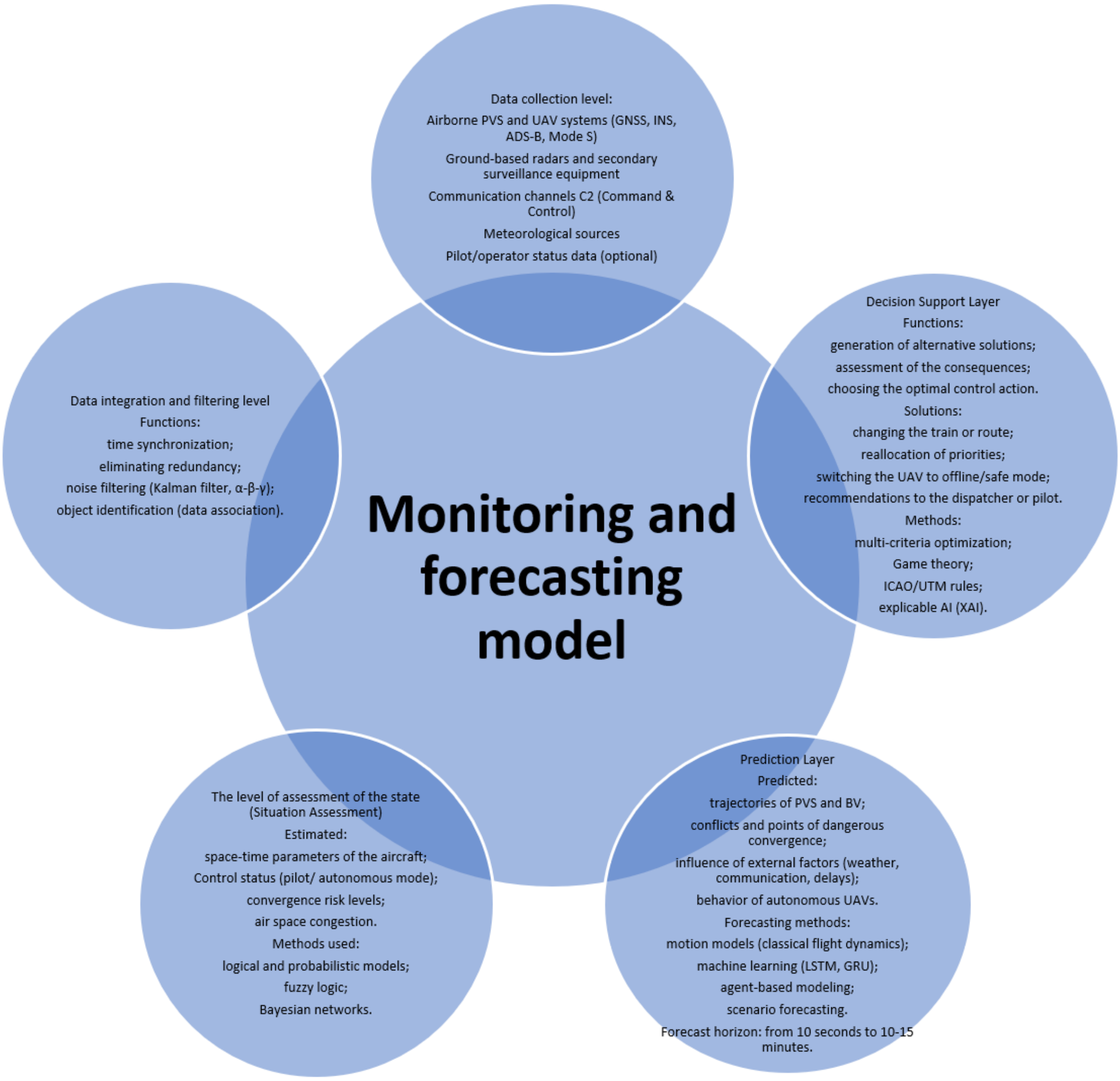


Figure 6. Interconnected levels monitoring and forecasting model.

The general state of the joint management system is described by the expression:

$$X(t) = \left[X_p(t), X_b(t), X_e(t)\right],$$

where $X_p(t)$- vectors of the status of manned aircraft, $X_b(t)$- vectors of the state of unmanned aircraft, $X_e(t)$ - the parameters of the external environment.

The expression is valid for manned and unmanned aircraft:

$$X_i(t) = [x_i(t), y_i(t), z_i(t), v_i(t), \psi_i(t), \gamma_i(t)]1^T$$

where, $x_i(t), y_i(t), z_i(t)$ - spatial coordinates, $v_i(t), \psi_i(t), \gamma_i(t)$- speed, course, trajectories.

The dynamics of aircraft movement described in (3) defines the monitoring process, which is described: $y_i(t) = h_i\left(x_i(t)\right) + v_i(t)$,

where $y_i(t)$- measurement vector (radar, telemetry, ADS-B), $v_i(t) \sim N(0, R)$- Gaussian measurement noise, where $x_i(t) = E[x_i(t) : Y_i(t)]$- the method of optimal filtering of aircraft states.

The forecast of the conditions of the aircraft in the interval Δt is formed by:

$$x_i(t+\Delta t) = \Phi_i\big((\Delta t)x_i(t)\big) + \int_t^{t+\Delta t} \Phi_i(t-\tau)\,\mathrm{B}_i u_i(\tau) dr,$$

where Φ_i, B_i – state transition and control matrices, where a training model is used for the UAS:

$$x_i(t+\Delta t) = \mathbf{M}_{Mi}(x_i(t), c_i)$$

With the probability of a conflict described in (4), the integral risk level is determined by:

$$R_{ij} = \int_{t_0}^{t_0+T_p} p_{ij}^{conf}(t)dt$$

Accordingly, the decision-making task is formulated as a multi-criteria optimization.:

$$U^* = argmin_{U\epsilon\Omega_1}\{\alpha_1 R_{conf} + \alpha_2 T_{delay} + \alpha_3 C_{load}\}\mathrm{m}$$

$R_{conf}, T_{delay}, C_{load}$- total risk of conflicts, delays, and workload on the dispatcher, α_k- weight coefficients.

The coordination and communication model is designed to ensure coordinated, safe and effective management of MAS and UAS in a dynamically changing environment with limited decision-making time and possible failures of communication channels and data uncertainty.

The model is considered as a multi-level human-machine system, including control subjects (pilots of the air defines system; UAS operators; autopilots, AI modules and control objects (air defines systems and UAS), airspace, weather conditions.

Decision-making is carried out within the framework of a distributed model, where:

- person makes high-level decisions even in critical situations.;
- automated systems perform routine and high-speed operations;
- intelligent agents offer alternatives and forecasts.

The key principle is the adaptive allocation of responsibility between humans and automation, depending on the complexity and risk of the situation [FAA 2020, SASAR 2021].

The model provides for: mechanisms for detecting conflicts and failures; redundancy of communication channels; transition of the UAS to safe autonomous modes; support for situational awareness of operators and pilots.

In general, the model of coordination and communication in the decision-making system for the management of manned and unmanned aircraft is an integrated human-machine architecture that ensures coordinated interaction between humans and automated controls based on continuous information exchange, adaptive distribution of functions and multilevel coordination of actions.

The basic principles are the organization of a single information space, multi-level coordination and adaptive communication.

Security mechanisms are provided by proactive (preliminary modelling of interaction scenarios; allocation of dynamic separation zones, forecasting of conflict situations) and reactive (time and space separation, immediate response protocols, escalation of decision-making in emergency situations

The effectiveness of the model should meet the criteria of reaction time to changes in the air situation, safety indicators (number of conflict situations), the capacity of mixed airspace and the reliability of communication channels.

Figure 7 shows a conceptual diagram of the coordination and communication model, and Figure 8 shows the components of the decision support system [Clothier R., Walker R. 2015, Cummings M. L., Bruni S., Mercier S. 2017].

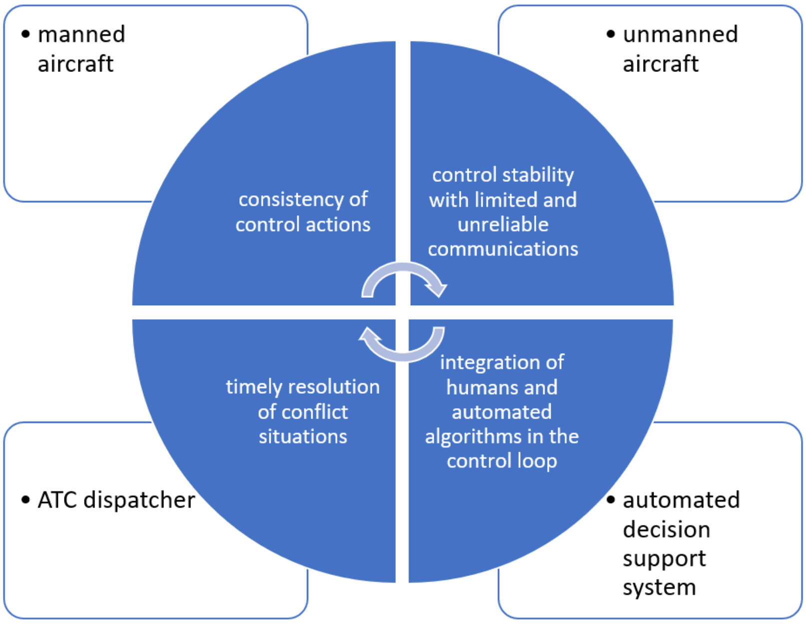


Figure 7. Conceptual diagram of the coordination and communication model

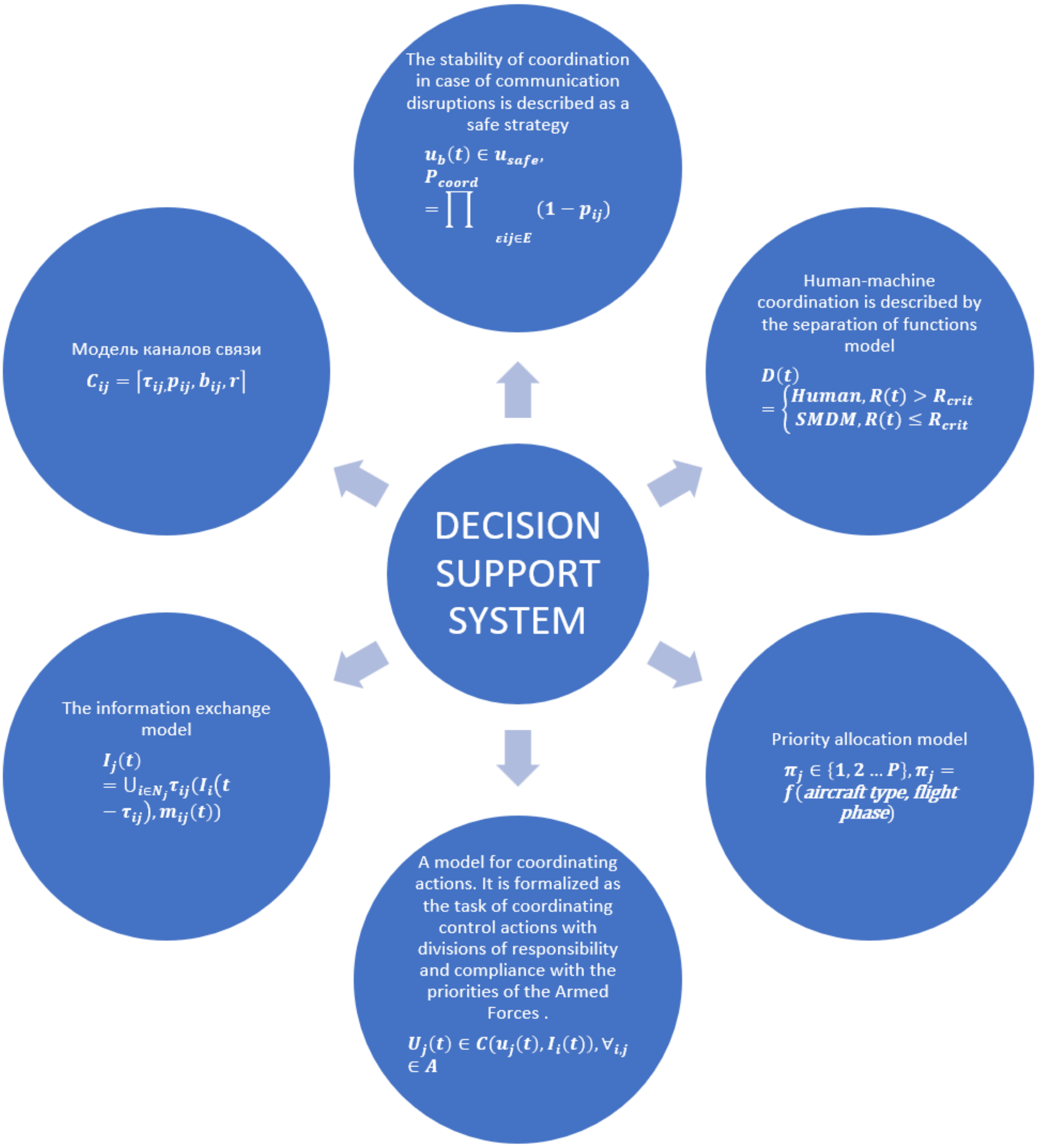


Figure 8. Components of the decision support system

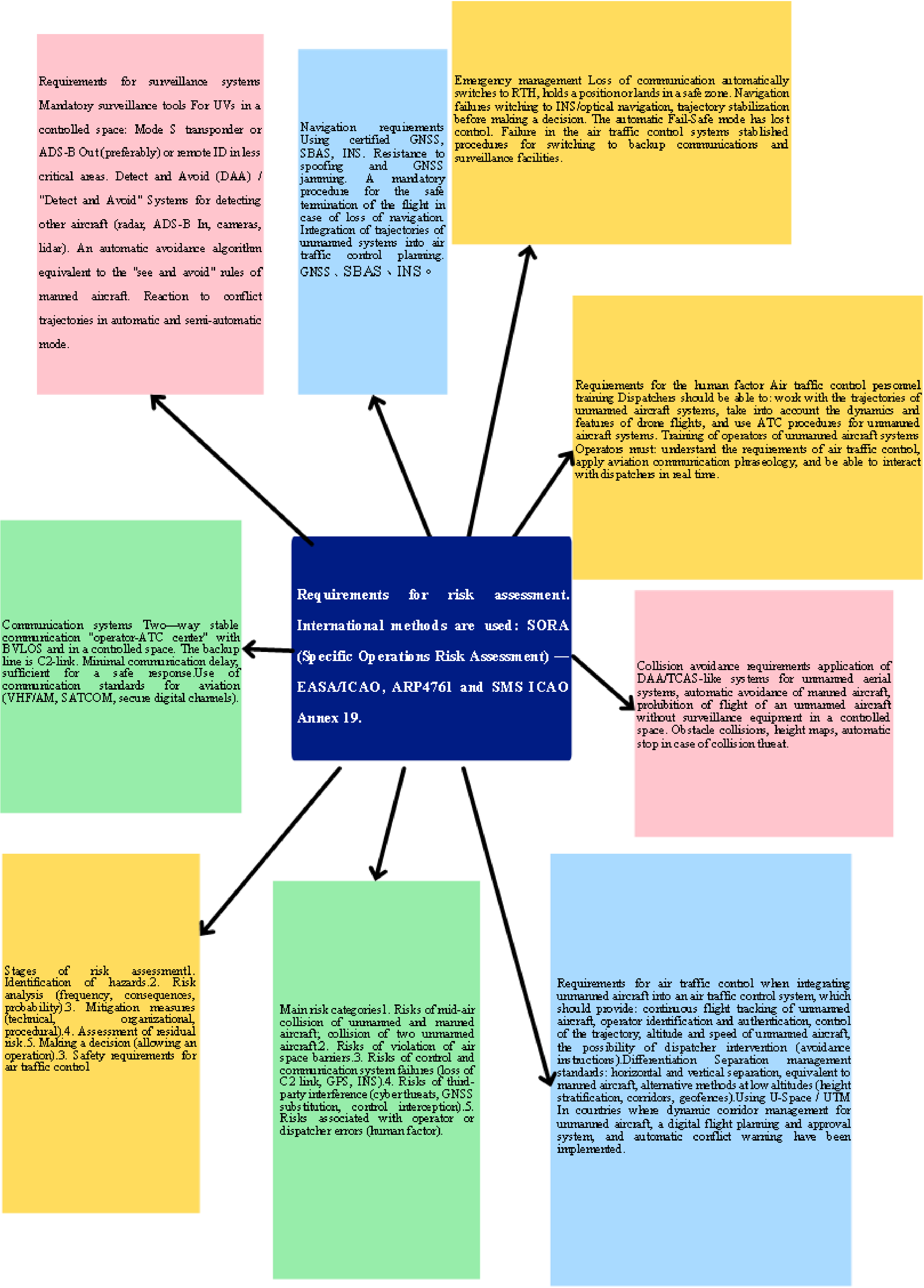
4. Risk assessment model

The task of risk assessment is formulated as determining a quantitative indicator reflecting the likelihood of a dangerous situation and the severity of its consequences under given flight conditions. Based on the obtained risk value, a management solution should be formed aimed at reducing the level of danger to an acceptable value. Improving the flight safety of manned and unmanned aircraft in conditions of increasing air traffic intensity and a more complex operational environment requires the use of intelligent decision-making systems based on a formalized risk assessment. One of the key tasks of such systems is the timely identification and quantification of factors that can lead to dangerous and emergency situations. Depending on the nature of the occurrence and the area of impact, risk factors are grouped into the following groups:

- technical factors characterizing the current state of on-board systems, equipment reliability and stability of control and communication channels;
- the human factor reflecting the level of training, the psychophysiological state and the cognitive load of the pilot or operator of an unmanned aircraft;
- environmental factors, including meteorological conditions, terrain features, and the presence of external disturbing influences;

- operational factors related to flight modes, air traffic density, and airspace restrictions;
- information factors that determine the reliability, completeness and timeliness of data entry into the management system.

This division makes it possible to ensure the modularity of the model and simplify the adaptation of its structure to the specific operating conditions of PVS and UVS. In real-world aircraft operating conditions, the input information about the state of the system and the external environment is incomplete and uncertain. In this regard, the model provides for the use of fuzzy logic methods and probabilistic models that allow for interval and linguistic parameter estimates. The use of these methods increases the model's resistance to measurement errors and provides a more adequate representation of the risk level in conditions of uncertainty. The developed multifactorial risk assessment model is integrated into the decision-making system and is used to predict the development of dangerous situations and the formation of control actions. Depending on the value of the integral risk indicator, the system can issue warnings, limit the permissible flight modes, or initiate a transition to safe or emergency control mode. A special feature of the model's application for unmanned aircraft is the need to take into account delays in communication channels and the level of autonomy of the control system, whereas for manned aircraft the influence of the human factor plays a key role. A multifactorial risk assessment model designed for use in decision-making systems for the management of manned and unmanned aircraft. The model provides a comprehensive account of heterogeneous risk factors and allows you to form informed management decisions in conditions of uncertainty and a dynamically changing environment. For unmanned aircraft, the key factors are the stability of communication channels and the level of autonomy, while for manned aircraft, the main focus is on minimizing the impact of the human factor. The unified structure of the model makes it possible to take these features into account by adaptive adjustment of the weighting coefficients [ICAO 2019, EOROCONTROL 2020, Moiseev N. N. 2014, Kuchar J. K., Yang L. C. 2000].



Requirements for risk assessment. International methods are used: SORA (Specific Operations Risk Assessment) — EASA/ICAO, ARP4761 and SMS ICAO Annex 19.

Requirements for surveillance systems Mandatory surveillance tools For UVs in a controlled space: Mode S transponder or ADS-B Out(preferably) or remote ID in less critical areas. Detect and Avoid (DAA) / "Detect and Avoid" Systems for detecting other aircraft (radar, ADS-B In, cameras, lidar). An automatic avoidance algorithm equivalent to the "see and avoid" rules of manned aircraft. Reaction to conflict trajectories in automatic and semi-automatic mode.

Navigation requirements Using certified GNSS, SBAS, INS. Resistance to spoofing and GNSS jamming. A mandatory procedure for the safe termination of the flight in case of loss of navigation. Integration of trajectories of unmanned systems into air traffic control planning. GNSS、SBAS、INS。

Emergency management Loss of communication automatically switches to RTH, holds a positionorlands in a safe zone. Navigation failures witching to INS/optical navigation, trajectory stabilization before making a decision. The automatic Fail-Safe mode has lost control. Failure in the air traffic control systems stablished procedures for switching to backup communications and surveillance facilities.

Requirements for the human factor Air traffic control personnel training Dispatchers should be able to: work with the trajectories of unmanned aircraft systems, take into account the dynamics and features of drone flights, and use ATC procedures for unmanned aircraft systems. Training of operators of unmanned aircraft systems Operators must: understand the requirements of air traffic control, apply aviation communication phraseology, and be able to interact with dispatchers in real time.

Communication systems Two—way stable communication "operator-ATC center" with BVLOS and in a controlled space. The backup line is C2-link. Minimal communication delay, sufficient for a safe response.Use of communication standards for aviation (VHF/AM, SATCOM, secure digital channels).

Collision avoidance requirements application of DAA/TCAS-like systems for unmanned aerial systems, automatic avoidance of manned aircraft, prohibition of flight of an unmanned aircraft without surveillance equipment in a controlled space. Obstacle collisions, height maps, automatic stop in case of collision threat.

Stages of risk assessment1. Identification of hazards.2. Risk analysis (frequency, consequences, probability).3. Mitigation measures (technical, organizational, procedural).4. Assessment of residual risk.5. Making a decision (allowing an operation).3. Safety requirements for air traffic control

Main risk categories1. Risks of mid-air collision of unmanned and manned aircraft; collision of two unmanned aircraft2. Risks of violation of air space barriers.3. Risks of control and communication system failures (loss of C2 link, GPS, INS).4. Risks of third-party interference (cyberthreats, GNSS substitution, control interception).5. Risks associated with operator or dispatcher errors (human factor).

Requirements for air traffic control when integrating unmanned aircraft into an air traffic control system, which should provide: continuous flight tracking of unmanned aircraft, operator identification and authentication, control of the trajectory, altitude and speed of unmanned aircraft, the possibility of dispatcher intervention (avoidance instructions).Differentiation Separation management standards: horizontal and vertical separation, equivalent to manned aircraft, alternative methods at low altitudes (height stratification, corridors, geofences).Using U-Space / UTM In countries where dynamic corridor management for unmanned aircraft, a digital flight planning and approval system, and automatic conflict warning have been implemented.

Figure 10. Risk assessment team

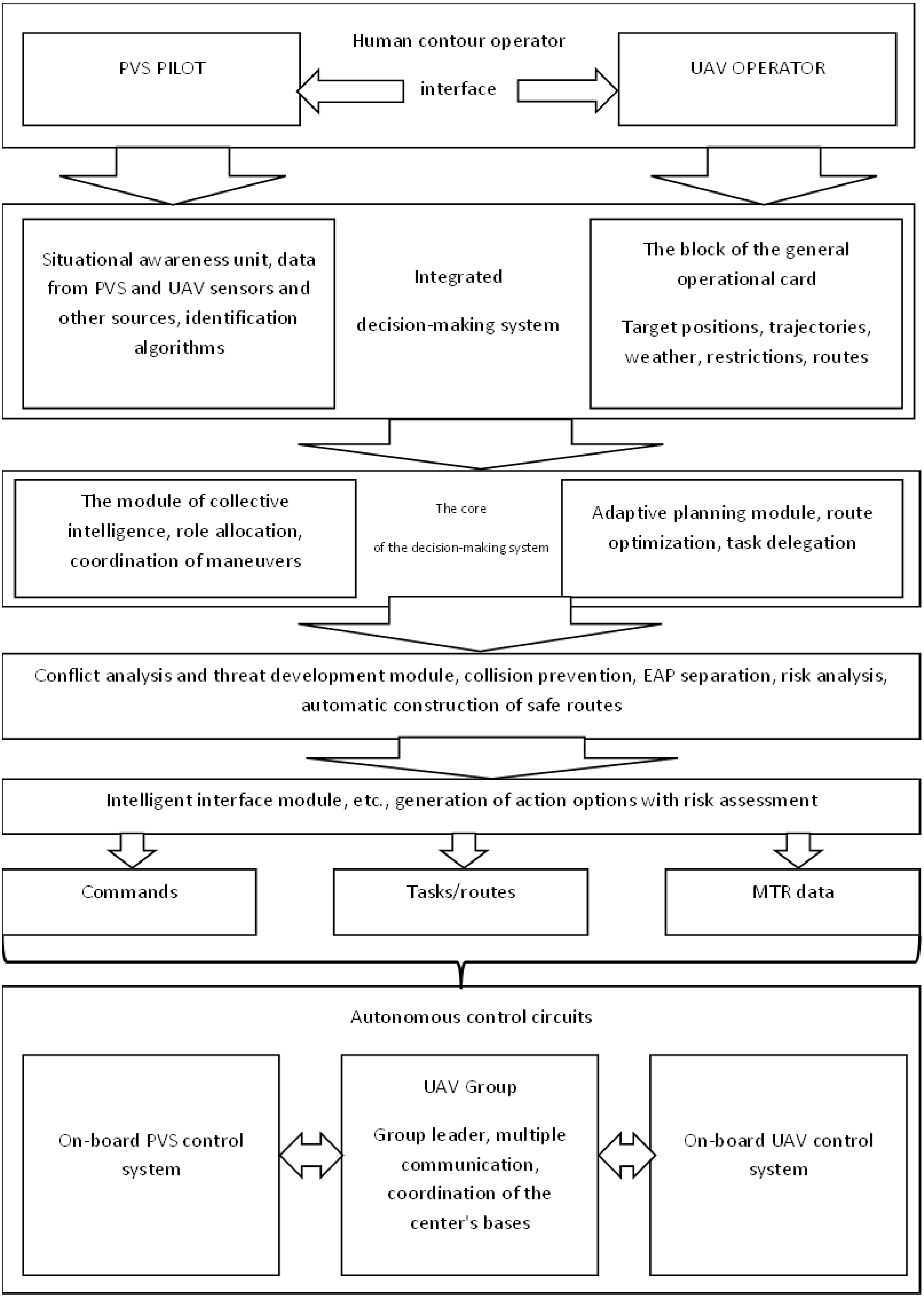


Figure 11. General model of Integrated decision-making system

5. General conclusions

The presented article develops and substantiates a set of interrelated models that form the methodological and algorithmic basis of an intelligent air traffic control system for manned and unmanned aircraft in conditions of high dynamism, uncertainty and heterogeneity of the information environment. The dynamic model of airspace allocation allows for an adaptive approach to managing the structure and parameters of airspace use based on the current and predicted state of the air situation. Unlike traditional static schemes, the proposed model provides a real-time redistribution of airspace, taking into account user priorities, safety constraints and aircraft characteristics, which helps to increase capacity and reduce air traffic conflict. The monitoring and forecasting model ensures the continuous formation of a holistic view of the state of the controlled system and the external environment through the integration of data from on-board, ground and external information sources. The use of predictive assessments allows you to move from reactive to proactive management, providing proactive identification of dangerous trends and increasing the time reserve for making management decisions.

The coordination and communication model formalizes the processes of information interaction between air traffic participants and the elements of the control system. Taking into account data transmission delays, limited bandwidth of communication channels and various levels of autonomy of unmanned aircraft makes it possible to increase the consistency of actions and stability of management in a distributed system architecture. The multifactorial risk assessment model integrates the results of the functioning of airspace allocation, monitoring, forecasting and coordination models, providing a quantitative assessment of the risk level taking into account technical, operational, human, external and informational factors. The use of weighted aggregation and uncertainty accounting methods makes it possible to form sound management decisions in conditions of incompleteness and inconsistency of information. The set of developed models forms a single scientific and methodological platform for intelligent air traffic control, which ensures an increase in the level of safety, adaptability and efficiency of aviation systems. The results obtained create a theoretical and practical basis for the further development of automated and autonomous air traffic control systems in conditions of joint operation of manned and unmanned aircraft [Pinto Neto E. C., Baum D. M., Almeida Jr. J. R., Camargo Jr. J. B., Cugnasca P. S. 2022, Valavanis K. P., Vachtsevanos G. J. 2015, Balas A. V. 2016].

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