Air Navigation: The Classification of Airborne Vehicles in the Air Traffic Management System*

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Abstract. The article considers the classification of airborne vehicles in the automated air traffic control system, which is essential for improving the level of air traffic safety. Proposed is a new method of airborne vehicles' classification which differs from the existing ones, as it is distinguished by integrated data processing from heterogeneous sources, formalizing the characteristics of airborne vehicles based on binary relationships and production models, the hierarchical structure of airborne vehicles' classification and the structural features of the singleton knowledge base. This article is the sequel to the earlier articles written by the authors on air navigation issues.

Keywords: airborne vehicles, air traffic control system, classification of airborne vehicles.

1 Introduction

Over the recent years, there has been a considerable growth in the number and variety of airborne vehicles used by various government departments, private companies, and individuals to meet the needs of the state, business, leisure, etc. Primarily, this growth is associated with the advent of unmanned aircraft (UMA).

At the same time, the number of violations in using airspace is constantly growing [1, 2]. Against this background, there has appeared a persistent tendency to cause possible harm to civilian objects with airborne vehicles in peacetime, that is, the possible terrorist use of airborne vehicles [3]. This situation is especially acute in airport areas.

Experts predict that the volume of the Russian market for UMA will have reached about $ 35 billion by 2035. Therefore, unmanned aircraft currently pose the greatest threat to civil aviation, as their owners try to take photos of airports or aircraft from an unusual angle. However, they do not stop doing it despite their awareness that their actions pose a real threat to the life and health of thousands of people and can cause damage amounting to tens of millions of rubles.

Specialists in protecting objects from airborne threats identify five types of problems caused by UMA in territories free from military conflicts [4]. The first problem is dangerous air miss with other airborne vehicles. The second problem is caused by flights over areas where the use of aircraft is prohibited or inappropriate, for example, over warehouses of combustibles and lubricants. The third problem is the criminal use of UMA (transporting drugs and smuggling into or from airports). Another threat is the collision of UMA with various buildings and structures at airports and adjacent territories. The use of UMA to commit terrorist acts in airport areas is the fifth type of threat.

Small-sized UMA (especially those of multicopter type) should be considered the main threat to civil aviation. Even seemingly insignificant on-board equipment weighing several hundred grams can cause considerable damage. Taking into account the fact that average payload's weight is from 10 to 30 percent of UMA's total weight, it can be concluded that UMA weighing from three to twenty kilograms present the main threat nowadays.

Consequently, low-altitude security is becoming increasingly important as an element of the overall effective response to air threats. Various technical means are currently used at airports for this purpose: fencing systems (fences, barriers), engineering barriers (barbed wire, difficult-to-surmount barriers), perimeter security alarms (passive and active infrared barriers, radio beam devices, and vibration-sensitive systems), monitoring and surveillance systems (video cameras, night vision devices). In specific cases, stationary or mobile technical inspection posts can be used as a means of increasing the safety level and expanding the controlled areas outside airports' outer security zones.

All these systems successfully fulfill their tasks. However, they are aimed exclusively at neutralizing ground-based threats nowadays. Perimeter protection complexes can be completely insulated even passing through places of inaccessible natural formations (water areas or ravines). Alarm systems tend to have high sensitivity and a low percentage of false positives. High-resolution radar stations and optoelectronic devices located at points of technical observation can detect UMA within several kilometers. However, these measures are no longer enough.

Technical solutions to the problem of UMA's intrusion consist of detection and suppression/interception services. The most effective means of detecting UMA is multisensor devices. Their functioning mode consists of processing signals from airborne targets through optical, acoustic, thermal, and radiofrequency channels. The combination of the characteristic features of a UMA in each of these channels creates its signature, which allows the system to distinguish UMA from birds or other types of aircraft. As soon as a target having the UMA signature is detected around the object in the near airspace (up to 1 km), the system turns on the alarm signal and starts to record the intrusion. A plan of further actions is developed by the airport security service: it can be taking people to a safe place, calling the police, bringing in their rapid response teams, or actively neutralizing the UMA. The UMA neutralization equipment is a block of jamming in the radio frequency range used to control the UMA from the operator's panel. Having lost contact with its operator, either a UMA returns to the point of departure or freezes hovering until its battery is discharged. Several UMA types can fly autonomously, according to a pre-programmed flight mission. In this case, jamming equipment from navigation satellites (GLONASS, GPS, Galileo) should be used.

Currently, a sufficiently great number of means of UMA's physical neutralization are in development. These are UMA interceptors with nets and pneumatic grenade launchers with nets inside their capsules. The prospects for the use of such means are still unclear, since in the first case the constant on-site duty of an experienced pilot of the UMA interceptors is required, and in the second case, the firing range of the capsules does not exceed 100 meters. Regardless of which method of neutralization is optimal from law and efficiency, ensuring low-altitude security is based on the timely detection of UMA (UMA-detection). The radius of UMA detection can be significantly increased if, in addition to the multisensor devices servicing the internal areas of the territory, airports are equipped with special radars. The radars tuned to detect exclusively UMA and having a range from 1 to 5 km can effectively protect airspace in airport areas. Equipping such systems with radio-frequency sensors will allow not only detecting UMA but also detecting the location of the intruding UMA's operator with the help of the triangulation method. The UMA operators' detention is the most preferred countermeasure in the airport area since jamming systems of radio and GPS signals are radiating facilities. Hence, their use at airports can lead to disruption of the navigation equipment of air traffic control services.

All the tackled problems also indicate the imperfection of legal acts in the field of airspace use. Also, one of the causes of violations of the rules for the use of airspace is the problem of the timely and correct classification of airborne vehicles (AV) including UMA.

2 Main part

The reliability of AV's identification and further classification is determined by the degree of data formalization and the quality of information about these vehicles' current behavior, their characteristics, the recognition process performed by experts, as well as other information needed to manage and control the airspace. Heterogeneous features are characterized by various types of metric evidence, reliability, rate of renewal, nature of changes, degree of mutual dependence, etc. The qualitative nature and uncertainty of some of the information features are eliminated by detailing or transformation on appropriate scales [5].

The feature information is characterized by stochastic and linguistic uncertainty [6]. The vagueness of information about airborne intruders is stochastic due to their intention not to reveal their planned actions using different types of interference, inaccurate measurements of AV parameters, poor quality of communication channels, etc. The use of technical parlance in the air traffic management service is the reason for the linguistic uncertainty of phrases in the decision-making process for airspace control. To describe many different situations in the air, the operator uses a limited number of words and phrases whose meanings are sometimes inaccurate, ambiguous, and incomplete.

The situational dynamism, a great number of features, and, accordingly, their possible disagreements, heterogeneity, uncertainty and incompleteness in the description of AV classes, data heterogeneity and the uncertainty of the classification process itself are often ignored while using traditional methods to formalize information about the air situation [7].

To identify an AV posing a threat, the cognitive approaches, in particular, fuzzy measures and sets are used. All AV features are represented by a basic linguistic or fuzzy variable and a generalizing linguistic variable corresponding to the production model and the formation of the knowledge base in the form of a set of linguistic variables [8]. However, this approach is more characteristic of a slowly changing air situation.

Attempts to present non-random information received from random sources lead to an uncertain decision on the classification of AV since most of AV features are formalized based on determinism. Fuzzy sets are used in case it is impossible to present information on AV using traditional methods. Fuzziness is described by fuzzy set adjectives. Given the rather uncertain nature of the information, the multi-signature method of AV can be used.

The currently adopted AV classification system does not allow for unambiguous determination of threat risks. To do this, it is necessary to determine the classification levels, the alphabet for AV classes, the list, and the information content of each class's features, i.e. the formation and formalization of AV reference features in a specific knowledge base.

The stage of processing information about the air situation, assessing its reliability, and forming AV current features precedes the stage of AV classification. Therefore, it is possible to find an effective solution to the problem of identifying AV, if image recognition methods and expert systems based on the automated collection and joint processing of information from various sources are used:

- radar stations of radio engineering units of the Armed Forces of the Russian Federation, including those providing recognition of AV classes and types;
- survey route radar systems of the Unified Air Traffic Management System of the Russian Federation;
- means of the Unified System of State Radar Identification of the Russian Federation;
- secondary radar equipment of domestic and international air traffic control systems;
- means of automatic independent airspace monitoring;
- radio engineering and electronic intelligence systems;
- sighting and command transmission stations that are part of command radio control aviation lines;
- means of planning the airspace use located at the centers of the Unified Air Traffic Management System of the Russian Federation;
- means, complexes, and systems of communication with AV.

The above-mentioned sources provide the following information and identification features:

- AV positioning data;

- data on the nationality of AV equipped with defendants of the state recognition system;
- individual or flight numbers;
- AV classes and types;
- data on the jamming environment (no interference; active interference; passive interference; combined interference);
- data on the situation on board the aircraft (does not suffer a disaster; suffers a disaster; the pilot has been injured; equipment failure; loss of orientation; fire; combat damage; the attack on the crew);
- AV quantitative composition;
- data on the AV location concerning the state border of the Russian Federation or the boundaries of restricted access facilities (does not violate; is in dangerous proximity; violates);
- planning and dispatch information.

Certain types of information and identification features can be assigned and entered into a complex of automation tools for controlling the use of airspace directly by the complex's operators.

The procedure of AV classification according to the degree of «danger» includes the following three stages:

- forming and dynamic updating knowledge bases of airspace control systems containing the information necessary to determine AV categories, first of all, the description of images of various AV categories;
- joint processing and generalization of positioning, flight, and individual features, as well as other information about AV, received from sources of various physical nature and serving various purposes;
- defining AV categories (actually the AV classification by the degree of their «danger»).

The knowledge bases formed at the first stage depend on the level of the airspace control system and can include data on consolidated daily flight plans, changes and supplements to it, the airspace structure, prohibitions and restrictions on its use, AV individual numbers and relevant data on each of them, various trajectory and signal-trajectory features, as well as other data necessary for determining AV categories.

Joint processing and generalization of information from various sources are aimed at creating a unique integrated image of every AV with the corresponding identification features. The determination of AV categories is carried out following the established regulations for every vehicle based on the information received about it and the information stored in knowledge bases.

Initially, the obtained positioning and flight data are identified with the daily flight plan. This process may take some time (depending on the degree of automation and reliability of the estimated information). Until a decision is made on whether the AV belongs to the scheduled ones, such a vehicle is considered unidentified.

If an AV is identified as «scheduled», then it is checked whether it follows the established flight modes. This check is conducted according to the algorithms of complexes of automation means of airspace use control. If the value of the controlled flight parameters is exceeded, the AV's «scheduled» category is changed to the «flight mode violator» category. All airborne vehicles that are not identified with the plan are then analyzed to define their possible belonging to unscheduled AV or those, which dominate objectives.

For objects that do not belong to any of the above-mentioned categories, the presence of a response signal is checked according to the system of state affiliation, the possibility of violating the state border or the boundaries of restricted access facilities is assessed, and aircraft belonging to the armed forces of foreign states are established. Depending on the presence or absence of these features, an airborne vehicle is either assigned one of these categories: «potentially dangerous AV», «border violator», «air enemy», or is considered unidentified. An AV having completely passed all the identification procedures is assigned an index and a unique number following the updated identification system.

The main requirements for the AV classification are as follows [7]:

- conformity of the formalized description of AV data to the mathematical class model;
- completeness and consistency of formalized data regarding the AV classification;
- obtaining results within a given time interval;
- the openness of the decision support system;
- the ability to use data from external sources of information.

There exist the information and cognitive approaches to formalize the decision-making processes.

The information approach is justified in systems designed to work under typical conditions, when the operator has enough time for an in-depth analysis of the situation and decision-making, and the computer saves information and is an auxiliary tool for evaluating solutions [9].

The cognitive approach is used in guidance systems characterized by a high degree of adaptability to external conditions. Therefore, knowledge representation is one of the main tasks in vehicles' classifications [10]. Formal or informal models are used to represent knowledge. The formal models are based on rigorous mathematical theory. Each informal model is developed for a specific knowledge domain. Conclusions in informal systems are largely subjective. The main methods of knowledge representation are based on the logical, frame, and production models, neural or semantic networks. The formalization of decision-making tasks in AV classification is characterized by incomplete or inaccurate information, that is, uncertainty. It is proposed to use the theory of fuzzy sets to take into account the uncertainty of information.

According to the analysis, the production models are most suitable for the tasks of AV classification. In general, products are threefold: <product name> <condition (α)> <expression (β)>. Products are close to the logical models and allow organizing effective output procedures on them. They reflect knowledge more clearly than the other models. The absence of strict restrictions makes it possible to change the interpretation of product elements.

Decision-making based on the principle of the causal relationship between informational features and the result can be described in a natural language and formalized as a set of logical statements. The class of a vehicle is obtained using logical inference mechanisms based on:

- fuzzy production rules;
- multi-criteria selection algorithms;
- use case and choice by analogy (fuzzy recognition of situations).

The decision on AV classification consists in the comparison of the current values of the observed vehicle's properties with the reference pattern. For this purpose, the degree of similarity or the distance between the vehicles is calculated. The AV's correspondence to a certain a priori class is chosen according to the rule: the sum of the distances from a certain class S* to all the other classes Si is minimal. The similarity measures proposed by Lukasevich, Tanimoto, etc. are used to determine the degree of similarity. However, sometimes it is problematic to use the selection method by analogy to solve the problem of classifying AV with incomplete information due to a change in the number of obtained features over time. The difference between the features' current dimension and the reference pattern does not allow comparison. But the selection method by analogy in combination with other methods provided that there is sufficient information to make a decision can bring good results in AV classification.

It is proposed to use a combined approach for the formal presentation of knowledge according to the AV classification: fuzzy production models with a developed output instrument, models with deterministic logical inference based on ordinary Boolean logic and the use of the selection method by analogy. This requires the development of two logical inference mechanisms – the deterministic one and the one under fuzzy conditions, namely:

- justifying the inference mechanism ensuring the formation of proposals for automated decision-making with insufficient information;
- synthesizing the mathematical description of AV classes by comparing the reference and current values of features, determining AV classes according to the chosen proximity criterion or using selected inference mechanisms;
- assessing the degree of conformity of the obtained AV classes developed at the conceptualization stage.

To describe the behavior of an AV, it is proposed to use the following group of features:

- the spatial position of the vehicle;
- the composition of the planning and dispatching information for the AV;
- the AV's controllability from the ground;
- the availability and composition of visual information about the AV;
- current information according to the primary location data;
- trajectory information.

We intend to describe each class of AV with its own set of quantitative and qualitative features [11, 12]. Quantitative features can be evaluated and quantified against each other. Qualitative features allow for a semantic description of vehicles' properties. According to the degree of significance, the features will be divided into groups, and AV will be classified separately for each group based on experimental data or expert estimates. Features are represented in binary space by dichotomizing data in each group [5].

Dichotomization is a sequential decomposition of the generalized feature A_i into the space of partial α_{ij}, in which each partial feature is represented in binary form («1» or «0»). This corresponds to the unit value of the membership function (singleton). The partial features α_{ij} of an AV's behavior are collected in groups A_i according to their types or sources. This approach allows switching from linguistic variables in the knowledge base to Boolean ones, i.e. defining them in a single dimensionless metric knowledge base.

The information features describing AV's behavior are as follows:

- A_1 – spatial position (α_{11} on the route, α_{12} near borders or prohibited areas, α_{13} in prohibited areas, α_{14} in areas not listed above);
- A_2 – scheduled dispatch information (α_{21} there is planned information about AV, α_{22} there is no planned information about AV, α_{23} there is planned information indicating violation, α_{24} there is planned information from the military dispatcher);
- A_3 – controllability from the ground (α_{31} there is communication, the crew executes commands, α_{32} there is communication, the crew does not execute commands, α_{33} there is no communication);
- A_4 – trajectory features (α_{41} high-speed AV, α_{42} low-speed AV, α_{43} maneuvering AV, α_{44} with constant motion parameters, α_{45} AV at low altitude, α_{46} AV at high altitude);
- A_5 – interference features (α_{51} AV interferes, α_{52} AV does not interfere).

The information features of recognition and secondary location are as follows:

- A_6 – responds in the RBS system (α_{61} in A mode, α_{62} in C mode, α_{63} in the 1st mode, α_{64} in the 2nd mode, α_{65} response code 7500, α_{66} response code 7600, α_{67} response code 7700, α_{68} responds with the alarm signal, α_{69} response codes 7711-7717, 7721-7727, α_{610} does not answer in the RBS systems);
- A_7 – the ASDE system's data (α_{71} decision was not made, α_{72} unknown, α_{73} interceptor, α_{74} of particular importance, α_{75} friend, α_{76} simulated enemy, α_{77} jammer of the simulated enemy, α_{78} enemy, α_{79} jammer, α_{710} suspicious AV).

We represent the AV classification procedure in the form of a graph, where α_{ij} are features, β_{mn} is the AV's class, i is the group of features, j is the current number of features in the group, m is the classification level, n is the current class number at this level.

The binary feature of space allows creating a matrix of correspondence of features and indices of AV affiliations (knowledge matrix) and then switching from linguistic variables in the knowledge base to Boolean ones.

The incompleteness of information on AV sometimes does not allow unambiguous identification of such vehicles. That is, it is necessary to expand the list of indices and automate the process of making appropriate decisions based on the available information. We introduce such a hierarchical system of the levels of AV classification.

According to the degree of threat and the need for action taken by the air traffic services concerning a specific AV (the first level):

- regular situation: no additional actions by officials of the air traffic control authorities are needed;
- activities by the competent authorities are not needed; additional attention or additional information is needed;
- •equired is an immediate set of measures taken by the appropriate authorities.

At the second level, AV is identified by their affiliation. At the third level, AV is identified by the main features (that is, they are assigned the current indices of affiliation). The fourth level is the identification of AV by additional features.

Some β_{mn} classes are determined automatically by deterministic features, others have a probabilistic or fuzzy character, and still others are formed by operators based on non-formalized data:

- according to the degree of threat (β_{11} air target, β_{12} air danger, β_{13} AV needs attention, β_{14} ordinary AV, β_{15} unidentified AV);
- according to AV's affiliation (β_{21} friend, β_{22} foe, β_{23} neutral, β_{24} military, β_{25} civilian, β_{26} unidentified);
- according to the main features (β_{31} AV with a recognition signal, β_{32} AV violating the state border, β_{33} AV on request, β_{34} AV violating the procedure for using airspace, β_{35} enemy, β_{36} AV without a recognition signal);
- according to additional features (β_{41} friendly interceptor, β_{42} responds in the 3rd mode, β_{43} aircraft number in the RBS system, β_{44} responds in the 40D system, β_{45} responds in the RBS system, β_{46} jammer, β_{47} training target, β_{47} control target, β_{49} «friend» response, β_{410} AV constituting a plausible threat, β_{411} AV constituting a confirmed threat, β_{412} AV's nationality).

Thus, the introduced hierarchical classification system of AV allows:

- identifying hazardous AV requiring special attention at the first level;
- comparing the existing legal system of AV classification according to affiliation indices with modern requirements for the definition of AV classes;
- ensuring the unambiguous conversion of data on AV classes in the data exchange on the air situation with neighboring states.

The large-dimensional matrix is used to unambiguously compare the available features of the proposed AV classes. To reduce its dimensionality and to compare AV's behavior features with affiliation indices, the corresponding inference equations are proposed for each of the classification levels.

The α_{ij} features can be entered automatically by the program simultaneously with the formation of records or after the initial data processing by operators:

- α_{1j} are formed according to the results of calculating the distance to the corresponding areas, the border line and comparison with the limit values;
- α_{2j} are entered manually or are formed by comparing the entered estimated information with the response codes in the RBS system (α_{21}) or comparing the estimated information with the current radar (α_{23});
- α_{3j} can only be entered manually according to the notification of the air traffic authorities (α_{33} is generated automatically when the α_{66} feature is received);
- α_{4j} are generated automatically according to the analysis of motion parameters according to radar observation data;
- α_{51} is entered manually or automatically when accompanied by a jammer using the triangulation method;
- α_{6j} are generated automatically according to the results of radar recognition (features α_{61}, α_{62}, α_{61}-α_{67}, α_{69} – according to the data in the RBS system, features α_{63}, α_{64}, α_{68}, α_{610} – according to the data in the 40D system).

The features for the classification of airborne vehicles are as follows:

- received automatically (α_{11}, α_{12}, α_{13}, α_{21}, α_{22}, α_{23}, α_{24});
- entered manually (α_{31}, α_{32}, α_{33}, α_{51}, β_{34}, β_{410}, β_{411}, α_{41}, α_{42}, α_{43}, α_{44}, α_{45}, α_{46}, α_{51}, A_6, A_7).
- α_{7j} features are obtained through data exchange lines with the ASDE system.

The following methods are used to obtain features automatically:

- α_{11}, α_{21}-α_{23} – the automated «correlation plan – track» procedure;
- α_{12}, α_{13} – calculation of distances to areas and boundaries;
- α_{41}-α_{44} – according to the secondary processing of radar information;
- α_{45}, α_{46}, A_6 – according to the data of radar observation through the channels of the primary and/or secondary radar;
- α_{51} – passive radar systems experience the influence of active interference sources (concerning passive jammers, a feature can be entered only semi-automatically);
- A_7 – conversion of ASDE message formats to the corresponding class formats.

Features carry objective and determinate data from the moment they are received or need additional actions and checking overtime to gain confidence.

The determinate features α_{31}-α_{33}, A_6 are objective and unambiguous, α_{12}, α_{41}-α_{46} need an initial definition of threshold indicators for designating them as deterministic.

Features of probabilistic confidence need other information elements to make it comprehensive: comparing current radar information with estimated information (α_{21}-α_{24}), secondary processing algorithms' sensitivity to maneuvers (α_{43}, α_{44}), etc. That is, the decision on AV depends on the quality of information and the degree of its dependability.

The information on the air situation in terms of its composition and content includes the value of AV's positioning in space and the parameters of their movement (positioning information about AV), as well as semantic (meaningful) information about AV and the air situation as a whole.

The semantic information about AV includes:

- the feature of defining AV's state or departmental affiliation;
- AV's affiliation index;
- AV's type (class);
- features of AV's actions (presence of maneuvering and its type, jamming and its type, etc.);
- the quantitative composition of a separate group of vehicles.

The processing of various kinds of data (trajectory (positioning) obtained through state recognition channels, secondary (flight) location, estimation, dispatching, and notification) becomes semantically relevant.

As the analysis of publications shows, the problem of assessing the quality of data, especially semantic data, for AV classification, has not been completely solved yet. The methods for assessing the quality of radar data to determine the location of air targets are best known [13]. The quality of radar data, divided into coordinate and non-coordinate, is usually assessed by completeness, accuracy, reliability, and efficiency.

To correctly determine an AV's location, the coordinate radar data will have the degree of accuracy to solve the problem to the specified probability. The pace of obtaining radar data should be consistent with the control cycle and allow solving the problem taking into account the time delay for data.

Non-coordinate information is evaluated by only one qualitative indicator – reliability, as a measure of the available data's correspondence to the facts. The reliability of the data used during decision-making determines the probability of a correct decision.

To identify airborne threats, a comprehensive assessment of the quality of radar data is necessary, which is based on partial indicators (completeness, accuracy, reliability) and temporal indicators.

The most difficult task is to assess the information's completeness. So, the following indicator [14] can be used to decide on the recognition of situations:

$$Y = \sum_{i=1}^{Q} \eta_i \cdot R_i \cdot T_i,$$

in which Q is the number of features; ηi is the coefficient of the feature's importance; R_i is the indicator showing the reliability of the results of AV's detection; T_i is the indicator of the efficiency of AV's detection.

This formula takes into account all the features used in recognition. However, this approach cannot provide an adequate assessment of the completeness of AV classification. Therefore, the assessment of completeness should not equal to the total number of features, but the correspondence of features to characteristic features allowing AV's unambiguous classification. Therefore, in further studies, it is necessary to determine the reference composition of features for each class of AV and the measure of the available data's proximity to the standard of comparison.

3 Conclusion

The formalization of features' description of airborne vehicles is based on the principle of determinism. The proposed method of forming the set of features of airborne vehicles includes the definition of the generalized features of airborne vehicles' behavior, their dichotomization, and the definition of a reference set of features for each class of airborne vehicles. The correspondence matrix of features and airborne vehicles' affiliation indices is formed in the binary space of features. This allows switching from linguistic variables in the knowledge base to Boolean ones.

Proposed is the hierarchical four-level classification system of airborne vehicles. The introduced classification system allows identifying hazardous airborne vehicles that need operators' special attention and comparing the existing system of airborne vehicles' classification by affiliation indices with the modern requirements for determining air targets' classes.

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