Intelligent Control in Unmanned Autonomous Aerial Mobility Systems

Tetiana Shmelova[a], Dmytro Kucherov[a], Serge Dolgikh[a,b], Vasyl Kondratyuk[a] and Oleksandr Kutsenko[a]

[a] National Aviation University, Liubomyra Huzara ave., 1, Kyiv, 03058, Ukraine
[b] Solana Networks, 301 Moodie Dr., Ottawa, K2H 9G1 Canada

Abstract

The challenge of an intelligent, and efficient organization of autonomous groups of Unmanned Aerial Vehicles for the execution of complex multi-functional tasks has emerged as actual or even critical in a growing number of tasks, applications, and domains. The functional models of intelligent autonomous Aerial Mobility Systems include several essential domains: distributed group intelligence, including Intelligent Decision Support systems for preparation and execution of autonomous operations of groups of aerial units; navigations and communications; safety, security, and resilience to obstacles and faults; physical operation and others. Integration of these functional domains into an effective Operation, Control, and Management system can represent a number of essential technical challenges. The functional areas of distributed intelligent mobility, including the Virtual Leader model; navigations and communications; safety, security, and robustness were considered in detail. The analysis and discussion led to the conclusion that the safe, versatile, multi-functional, and efficient autonomous organization of Aerial Mobility Systems is possible based on the principles of interoperability, standardization, encapsulation, and intelligent control proposed in this work.

Keywords 1

Unmanned Aerial Systems, Intelligent Systems, autonomous systems, autonomous networks, distributed intelligence systems, discrete networks, protocol model

1. Introduction

The development of Unmanned Aerial Systems (UAS) based on Unmanned Aerial Vehicles (UAVs) is currently being carried out by most countries of the world. UAS can be effective in performing complex functions and executing complex tasks in civilian, security, and military including in monitoring and responding to emergencies and natural disasters, in agriculture, aerial photography, communications networks, and weather, air, and water monitoring. Employing unmanned aviation has several advantages compared to piloted by a human, namely: lower cost of operation, stability, and flexibility in performing targeted tasks, simplicity, and availability of technology; UAV-based solutions can be employed effectively and efficiently when manned aircraft are impractical, expensive or carry unjustifiable risks [1]. Until recently, the main direction of UAS development was multipurpose use, for example, control and protection of forests, nature reserves, ice reconnaissance, monitoring of the fire risk of large areas, and others. The development of new potential applications of UAS continues at an accelerating pace [2; 3].

IntelITSIS'2023: 4th International Workshop on Intelligent Information Technologies and Systems of Information Security, March 22–24, 2023, Khmelnytskyi, Ukraine
EMAIL: shmelova@ukr.net (Tetiana Shmelova); d_kucherov@ukr.net (Dmytro Kucherov); serged.7@gmail.com (Serge Dolgikh); kon_vm@ukr.net (Vasyl Kondratyuk); kutsenkooleksandrua@gmail.com (Oleksandr Kutsenko)
ORCID: 0000-0002-9737-6906 (Tetiana Shmelova); 0000-0002-4334-4175 (Dmytro Kucherov); 0000-0001-5929-8954 (Serge Dolgikh); 0000-0002-5690-8873 (Vasyl Kondratyuk); 0000-0003-2741-5559 (Oleksandr Kutsenko).

Due to natural limitations of the capacity of an individual UAV, for effective execution of some, larger scale tasks are practical to use collectives, teams, or groups of UAVs. The efficiency of UAV group flights in monitoring forest fires, search, and rescue operations, agriculture, monitoring crops, relaying communications, moving cargo, and monitoring large areas can be considerably higher than that of the solutions based on individual UAVs. Approaches and topics in collective (group) operation of UAVs were examined in [4 - 6]. Presently, there exist many approaches, concepts, and strategies for the organization of transport among the most promising being the development of Unmanned Aerial Mobility (UAM) [3; 5 - 7].

The development of these concepts and methods can be attributed to significant and concurrent advances in automation, including machine intelligence, and the development of unmanned aviation technology [2, 3]. For example, one of the emerging trends is Urban Air Mobility, with the principal goal of the organization of a safe and efficient aviation transport system in and around an urban area [3; 5] Accordingly, the development of methods, principles, and foundations of safe, coordinated, and effectively integrated UAV flights in a single air transport system is one of the main actual problems in contemporary aviation [3; 8 - 11]. The article considers the development of an autonomous intelligence System for the effective organization of UAV flights, the choice of a Virtual Leader to control a group of UAVs, navigation, and communications, ensuring flight safety on the examples of organizing flights in and around an urban area.

1.1. Related Works

Many of the studies in group operations of UAVs are guided by classical approaches to the organization of flights [12], such as the methods of classical control theory. The problems in the management of a group organized in the form of a “system” are considered, which implies a separate representation of the movement of an individual object of the group by a mathematical model for lateral and longitudinal movement of the center of gravity. This objectively raises the problem of developing some optimal route for the group and its individual elements. A number of works are devoted to solving the problem of route planning for both one UAV and a group of UAVs [3; 4]. The main goal of building a route for the ordered movement of the UAV is aimed at ensuring the safety of the movement of the group, which is provided by the support of the selected distances and the speed of movement of individual elements of the group [3; 4; 13].

In [14; 15] three control strategies based on a behavioral approach to the formation of a group of road-mobile robots were discussed. An overview of a number of Deep Learning and reinforcement learning methods for strap-down aircraft systems was presented in [16]. It also discusses the use of computer vision information for reinforcement learning while providing autonomous control and navigation of these systems. The experimental results of managing a team of 20 quadcopters with onboard orientation and control, each of which works autonomously with an external system for tracking and measuring the coordinates of the quadcopter were presented.

The architecture and algorithms for coordinating a team of quadcopters, organizing them into groups, and flying are based on the mixed-integer quadratic programming method [17; 18]. Three groups of algorithms are considered, including the aspects of autonomous navigation components and obstacle avoidance. In [19] a network approach to control the coordinated movement of autonomous vehicles was proposed. It describes algorithms of construction and preservation of a predefined formation by a group of autonomous vehicles following a specified trajectory. The downside of the approach is that at present, the control system has limited capabilities in terms of the number of managed vehicles [20; 21].

To overcome the difficulties of applying the classical control theory, approaches in control based on behavioral responses using neural networks were used [18]. Collective control of a group of mobile robots, software implementation, and leader-follower strategies while tracking a route was investigated in [19; 20]. A distributed protocol for collaborative control of UAV's group swarm capable of maintaining the group configuration under different conditions was discussed in [21]. In [22] operation of UAV groups in challenged and constrained conditions was examined, based on the attractive and repulsive fields. Examples of applications of potentially large-scale unmanned aerial autonomy can be found in the concept of UAM [2; 3; 23]. The emergence of high-performance communications and navigation technologies enables the operation of such vehicles in urban areas [1; 5].

The use of UAS in challenging tasks, applications, and conditions described above, with ever-increasing versatility and complexity, requires UAVs teams to work collaboratively and autonomously to perform complex and diverse tasks and missions with minimal human oversight due to limitations in scope and human capabilities, while maximizing safety, cost-effectiveness, quality, minimal environmental impact and fulfillment of other mandatory requirements and criteria [2; 23]. Meeting these expectations and requirements will be possible with the implementation of operational command and control systems capable of supporting versatile autonomous groups of UAVs performing a wide range of complex tasks and activities with a division of roles in a team and with minimal human supervision, supported by the highest level of safety standards [3; 20; 23].

However, contemporary unmanned aerial systems and technology have several essential barriers limiting their functionality, versatility, performance, and growth potential:

- The need for higher autonomy: current systems require significant and constant control by a human operator consuming significant resources in capacity, time, and cost.
- Hardwired to task: management systems are often designed for a specific task and may not allow easy retargeting to a different mission, application, or functional domain.
- Limited role support: the current level of unmanned aerial technology does not allow significant variation of the roles in a group or team collectively executing a complex task or activity.
- A predominance of proprietary management interfaces, functions, and protocols limiting interoperability of functions and components and accordingly, flexibility UAS.
- Limited autonomous intelligence.
- Constrained scalability: the span of applications is naturally restricted by the constraints on human and cost resources.

To address these challenges and limitations of the conventional technologies were examined models and systems that may allow greater independence (autonomy) in the execution of intelligent functions with several advantages in functionality, versatility, and efficiency and without limitations on the complexity of required functions based on concepts and approaches in functional autonomy; distributed group intelligence; functional versatility; robustness and security.

The contributions of the work are: an analysis of functional areas in the problem of organization of safe and efficient autonomous UAV operation as an integrated and integral system; a review and analysis of methods and approaches in distributed aerial intelligence and intelligent operation support systems; a review and discussion of problems and challenges in robustness, and security of autonomous aerial mobility systems; a protocol model of intelligent aerial mobility as a basis for development of functionally versatile, efficient and safe models and systems of unmanned aerial mobility.

2. Methodology

2.1. Methods and Approaches in Unmanned Aerial Mobility

There are different systems of UAV control, based on the level of autonomy of individual and group UAV operation and control. One can distinguish the following levels of autonomy:

1. Remote control by an operator of a UAV (remote pilot): least autonomy, higher responsiveness, and versatility
2. Autonomously controlled via onboard computers/programming before flight: least autonomy, lower responsiveness, and versatility
3. Semi-autonomously controlled via intervening actions of an operator and autonomous decision-making intelligence: medium level of autonomy.
4. Autonomously controlled via autonomous decision-making intelligence while in flight: the highest level of autonomy.

Different configurations of organization, management, and control over the operation of UAV groups are illustrated in Figure 1. Left: a single operator per aerial unit (dedicated remote pilot); an operator controlling a group of UAVs; a group of operators controlling a group of UAVs. Right: an operator controlling UAV leader or CDR (central drone repeater) passing commands to a group of UAVs; an operator to a virtual leader / VCDR (virtual central drone repeater) to a subgroup of UAVs. Additionally, in accordance with the autonomy levels defined above, the following configuration can be defined: semi- or fully autonomous operation of a single UAV; semi-autonomous operation of a group of UAVs (Level 3 autonomy); fully autonomous operation of a group of UAVs (Level 4 autonomy). Finally, fully autonomous configurations can be further subdivided into the subcategories:

- Hierarchical, i.e., with a leader or leaders assuming different roles in the group.
- Flat (without a leader, all units execute the same role.
- Virtual leader: a virtual (non-physical) configuration identified and executed by the members of the group.

Currently, UAVs are used to perform many tasks that were previously difficult to solve such as observation and monitoring missions in hard-to-reach places (forest, mountains, sea, rivers, lakes, big parks); monitoring forest fires; search and rescue operations; alternative performance of a difficult agricultural activity (aviation chemical work); relaying of communication signals in places where antenna coverage cannot be set because of terrain; for first aid to people in various life situations [1-4, 23]. The use of group drone flights increases the efficiency of these target tasks. The efficiency of group UAV flights in some operations is preferable such as monitoring forest fires, search and rescue operations, agriculture in crop processing, communication relay, and cargo movement. The main advantage of using UAVs is areas with extra high risks to humans or large and inaccessible areas with the necessity to control using single or group UAVs flights in cities or agricultural terrain [2, 3, 23].

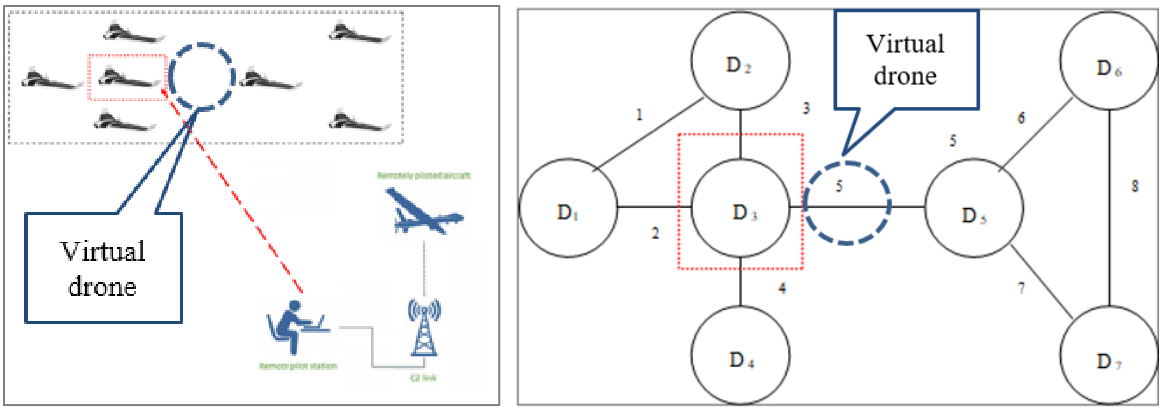

Figure 1: Control models in Unmanned Aerial Mobility

The use of fully autonomous single-unit or groups of UAVs opens a broad variety of applications as well as a principally new level of complexity of target tasks and missions reducing the requirement for critical human resources and balancing off certain disadvantages of UAV technology such as limited capacity [5; 23]. An obvious and sought-after in many applications additional advantage of this technology is faster, longer, and more thorough coverage of large spatial areas in urban and rural settings. To advance in the definition, design, and implementation of practical autonomous intelligent unmanned aerial systems, the following aspects of the autonomous operation have to be investigated and addressed in sufficient detail:

- Group configuration: definition, assumption and maintaining group formation, and configuration necessary for the execution of tasks in fully or near autonomous regime of operation.
- Navigation, orientation, and communications necessary for the execution of the task, including group configuration. Include in-group functions, as well as necessary options for external communications.
- Definition and support of functional tasks and processes necessary for the execution of group tasks.
- Capabilities, including intelligence for the execution of application-level tasks.
- Safety, robustness, resilience, and security.

While discussing all these aspects in sufficient detail may require sizeable, dedicated work, in the next sections some of them, as well as directions for integration of solutions into a platform for the development of an ecosystem of versatile, intelligent, effective, and efficient unmanned aerial systems are discussed.

2.2. Autonomous Group Mobility: Virtual Leader Model

A group of UAVs is considered a group performing a task that requires a stable formation. In the examples here it will be assumed that the groups are limited to 3–5 individual units, though it is expected that the approach can be readily adapted to larger groups via scaling. The virtual leader-follower structure in this case can be represented as an undirected graph. The number of vehicles can be increased by scaling. At the same time, the group acquires a network structure, the nodes of which are virtual leaders, relative to which real UAVs perform the task.

It is assumed that each unit has the appropriate on-board equipment to maintain communication and perform the task as intended. An aircraft of a quadrotor type was chosen as the base model. It is distinguished by high maneuverability and the ability to hover.

The basic model can be represented by a system of second-order differential equations that take into account the 3-dimensionality of space, i.e., written in the form:

$$\begin{cases} \ddot{V} = f(\dot{x}, \dot{y}, \dot{z}), \\ \ddot{\Omega} = f(\dot{\theta}, \dot{\phi}, \dot{\psi}). \end{cases} \quad (1)$$

In the system (1) the equations describe the dynamic of the group in the Descartes and Euler coordinates, respectively, with constraints on the angular coordinates: $|\theta| < \pi/2$; $|\varphi| < \pi/2$; $|\psi| \leq \pi$; $z > 0$.

A group is defined by a sphere of a radius r that contains the units in the group:

$$\boldsymbol{D = \{|p_i - p_j| \leq r, \qquad r > 0\}, i \neq j;\ i, j = 1, \ldots, N,} \quad (2)$$

where

r - the radius, N - the number of units in the group, |...| - Euclidean norm.

The coordinates of the virtual leader for a group of three units are determined by the middle of the segment connecting the centers of mass of the vehicles:

$$\boldsymbol{x_{vl} = \frac{x_{UAV_1} + x_{UAV_2}}{2}, y_{vl} = \frac{y_{UAV_1} + y_{UAV_2}}{2}} \quad (3)$$

In (3) it was assumed that the coordinates of neighboring vehicles are known, perhaps via a separate navigation function as discussed in Section 2.4. UAVs move along trajectories equidistant relative to the leader, when (2) i, j = 1, 2 is satisfied. The virtual leader then is the center of the formation in the (X, Y) plane that is a circle of a radius r, as illustrated in Figure 2.

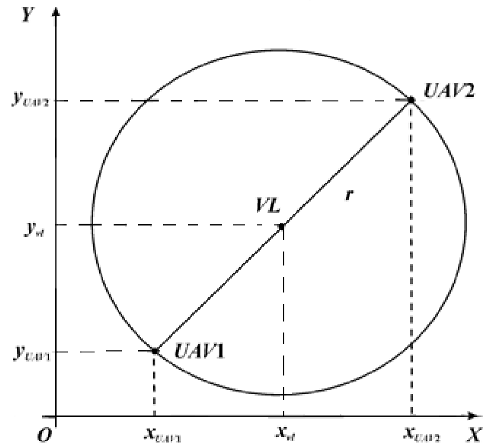

Figure 2: Calculation of the virtual leader coordinates in a 3-unit group

Next, we consider a four-vehicle group. As before, the coordinates of the virtual leader of the group can be found with:

$$\boldsymbol{x_{vl} = \frac{x_{UAV1}+x_{UAV2}}{2} + l(r - r_1),\ y_{vl} = \frac{y_{UAV2}+y_{UAV3}}{2} + l(r - r_2)} \quad (4)$$

In (4) x_{UAV1}, x_{UAV2}, y_{UAV2}, y_{UAV3}: coordinates of the physical members of the group in a triangle formation with sides a, b, c; r – the radius of the excircle of the formation.

$$r = \frac{p}{4\cos\frac{\alpha}{2}\cos\frac{\beta}{2}\cos\frac{\gamma}{2}} \quad (5)$$

where $p = \frac{a+b+c}{2}$, the angles α, β, γ: the opposites of the sides a, b, c; l – a positive factor, r_1, r_2 calculated as:

$$r_1 = \sqrt{(x_{UAV1} - x_{vl})^2 + (y_{UAV1} - y_{vl})^2}; r_2 = \sqrt{(x_{UAV3} - x_{vl})^2 + (y_{UAV3} - y_{vl})^2} \quad (6)$$

In the considered method, the virtual leader sets the trajectory of movement for the physical units in the group. The trajectory of the virtual leader itself is given by a preset route representing a sequence of points connected by segments.

2.3. Distributed Autonomous Group Intelligence

The method of virtual leader for autonomous groups of aerial units described in Section 2.2 is an example of an application of a general concept of Distributed Autonomous Intelligence. It can be defined by the following set of requirements:

- Distributed: the units in the group have the same level of intelligence, i.e., intelligent functions and execute the same or similar roles.
- Independence: the decisions of the units are taken independently based on the data obtained from other members and their own sources (navigation, visual orientation, etc.).
- Autonomy: control and/or connection to an external authority is not required for the successful execution of the flight function.
- Coherence and functionality: the models and protocols of establishing and maintaining the formation have to be functional under the requirements of distributed operation, independence, and autonomy in all flight situations.

Developing effective protocols of group operation and control satisfying the requirements of Distributed Autonomous Intelligence is an important contribution to the concept and practical approaches in versatile multi-functional autonomous UAS.

2.4. Navigation and Communications

As discussed earlier in this work, the concept of Distributed Autonomous Intelligence being instrumental in supporting truly autonomous versatile unmanned aerial systems, implies and requires access to sophisticated and effective navigation and communications functions by individual units in the autonomous group. Requirements for quality parameters (such as, accuracy, availability, reliability, integrity, etc.) of modern navigation systems are constantly strengthening. Innovations, such as sensor integration is one of the promising directions in addressing this essential need. It should be noted that an important basis for successful sensor integration is the redundancy of sensor information. There are four types of redundancy are proposed:

- Parallel redundancy
- Complementary redundancy
- Heterogeneous redundancy
- Analytical redundancy

Here we will discuss complementary redundancy in more detail. This redundancy occurs when two or more sensors with different operating principles and variable characteristics are used. Such sensors complement each other in such a way that the advantages of one of them may compensate for the deficiencies of the other and vice versa.

A combination of Inertial Navigation System (INS) and Global Navigation Satellite Systems (GNSS) is a typical example of complementary redundancy, since these systems are based on different physical principles, and to some extent complement each other. For example, in urban areas, the GNSS system is often unavailable due to signal blocking effects, which can be compensated for by navigation calculations. On the other hand, the navigation calculation maintains sufficient accuracy only over short distances traveled, and the GNSS system helps it reduce the accumulation of measurement errors with distance. In other words, GNSS maintains the relevance of navigation calculation results. Without a GNSS system, unwanted error propagation may become significant, especially when measuring changes in direction over time. Therefore, a combined use of these systems may allow, on the one hand, to limit the propagation of errors of the less accurate but more informative inertial system, and on the other hand, to increase the rate of information delivery to on-board consumers, significantly improving the resilience and reducing the noise component of errors of a high-precision satellite system. Integrated inertial-satellite navigation systems (ISNS) are widely used in world practice due to the following reasons:

- Flight control tasks require analog measurement of linear and angular flight parameters, or at least the quantization frequency of these parameters should be measured in tens of Hertz.
- However, the GNSS provides a frequency of quantization of position and speed signals of the aircraft with a frequency of 1 Hz (in the best case, 20 Hz), which is clearly insufficient. INSs can provide high rates of information output (up to 100 Hz).
- INSs are highly informative, i.e., they measure both linear and angular parameters, while GNSS measure only linear parameters (the aircraft position vector in some geocentric coordinate system and its velocity vector). In principle, GNSS can also be used to measure angular coordinates, but it may not be practical in all scenarios.
- Errors arising in INS and GNSS are of a different nature. INSs are characterized by an unlimited growth of errors in time, which can only be compensated for or corrected with an external correction mechanism. At the same time, the random errors of the primary measurements of the INS are quite well smoothed out with the help of integration operations. On the other hand, in the GNSS, calculations of the position and velocity vectors of the aircraft are not based on integration. Therefore, although there are errors in the output signals of the SNS with a high dispersion, they are limited, unlike the INS.
- GNSS signals have a high frequency and low power. Weak signal strength, multiple reflections of the received signal from the surrounding surfaces, ionospheric, atmospheric, and tropospheric interference can significantly reduce the «signal-noise» of the signal and consequently, the effectiveness of the GNSS receiver in such conditions. Radio engineering circuits for tracking the signals of navigation satellites can easily "lose" the satellite in the presence of active interference. On the other hand, INS are completely autonomous systems characterized by high interference resistance and reliability of the navigation solution.

Principal advantages and downsides of the discussed navigation systems are summarized in Table 1.

Table 1

Advantages vs. Challenges, GNSS, INS

Navigation System	Advantage	Downside
GNSS	• Higher accuracy • Errors are bounded	• Lower information yield rate (< 10 Hz) • Lacking angular orientation data • Lower resistance to interference
INS	• Higher information yield rate (up to 100 Hz) • Higher information content (including angular data) • Full autonomy • Higher resistance to interference and reliability	• Potentially unbounded accumulation of errors • Dependent on the accuracy of the Earth gravitational map

Thus, integrated ISNS combine the advantages of separate systems and eliminate their shortcomings. As a result, a navigation system with a high frequency of updating navigation parameters is obtained, a smooth flight path, good short- and long-term accuracy, and increased resilience, reliability, and integrity. The trend toward the use and implementation of integrated systems for positioning and navigation tasks is driven by the need for high-precision, lightweight, low-cost navigation systems, as well as technological advances that meet these requirements. Commonly used approach to optimal integration of INS and GNSS data are the Kalman filtering (KF) algorithms [24]. Kalman filter is an extremely efficient and convenient mathematical tool for combining the outputs of various sensors with noise for estimation of the state of a system with uncertain dynamics. Such noisy sensors can be both satellite positioning systems and inertial navigation systems, as well as auxiliary sensors, for example, speed sensors, magnetic compasses, altimeters, or radio navigation aids. Variables such as position, velocity, acceleration, orientation, and angular velocity of the vehicle are usually taken as the state of the system. Auxiliary variables for modeling time-correlated noise sources can also be included here. Uncertain dynamics include unforeseen obstacles that can be introduced by both humans and the external environment. This may also include unpredictable changes in sensor parameters. Traditionally, two types of Kalman filter are used in integrated navigation systems: linearized Kalman filter (LKF) and extended Kalman filter (EKF). LKF works using a linearized process model. This linearization is implemented by the first-order approximation of the Taylor series expansion. The same matrices of dynamics and measurements are used in the process. With EKF, the dynamics and measurement matrices can also contain non-linear elements and are calculated at each step. Thus, EKF can be more accurate than LKF, but requires higher computational capacity.

Another significant advantage of an autonomous configuration of an aerial group is that navigation and communications functions, including those discussed in this section, are mostly concentrated within the limited spatial span of the group, with massively reduced capacity and power requirements for navigation and communications, greatly reduced dependence on external sources of information and control and as a result, improved robustness, and security in operation.

2.5. Robustness, Resilience and Security

According to the UAM concept published recently [11; 12], an effective air navigation system in and around the city using UAVs must include:

- Execution of the targeted tasks
- Analysis and assessment of terrain for flights
- Determination of effective routes (with minimum risk and maximum safety).

The Intelligent Decision Support System ‘module (IDSS) allows UAV operators to control decision-making, to have effective support, and for autonomous flights to program and prepare actions of the UAV and autonomous groups, especially in an emergency according to the development of the flight situation. The organization of a safe and efficient UAM system depends on the intellectualization of existing systems and the synchronization of the actions of all operators of the air navigation system when performing UAV flights, and of the UAV group too. To organize the work of air navigation system operators, it is proposed to use intelligent decision support systems as an interactive computer system designed to support activities of operators / hybrid systems when making decisions in semi-structured and unstructured tasks, based on the use of models and data processing procedures and knowledge based on Artificial Intelligence technologies [24].

To integrate and synchronize the actions of operators, especially in an emergency, decision-making models under conditions of certainty, risk, uncertainty, and dynamic programming models, collaborative decision-making models are used. In the case of data accumulation (data enrichment - expert, experimental and statistical data), elements of AI are used to process data and obtain rational solutions to support operators (pilots, operators of UAVs, air traffic controllers, ground engineering services, IT specialists, another professional operator etc.). A scheme of an intelligent control module for the IDSS has been presented in Figure 3.

The IDSS has been developed to effectively solve different tasks in the smart city (monitoring traffic intensity; operational emergency services; performance of search and rescue tasks; photo/video monitoring; mobile Wi-Fi relay points; delivery and movement of goods, etc.). The effectiveness of the use of UAVs for the modern city as a "smart city" has some problems with the presence of obstructions and restricted areas for UAV flights: the presence of objects of infrastructure, buildings, roads, and construction; the existence of recreation areas and natural areas; the existence of "forbidden" or "dangerous" zones; planning routes of UAV flights after an existence of UAV-tracks and flight areas of UAVs. To assess the safety of UAV flights in the city Maps of obstructions in and around an urban area were made. The quantitative values of UAV flight "risks" were obtained using a combination of the Expert Judgment Method (EJM) and Fuzzy logic [2; 23].

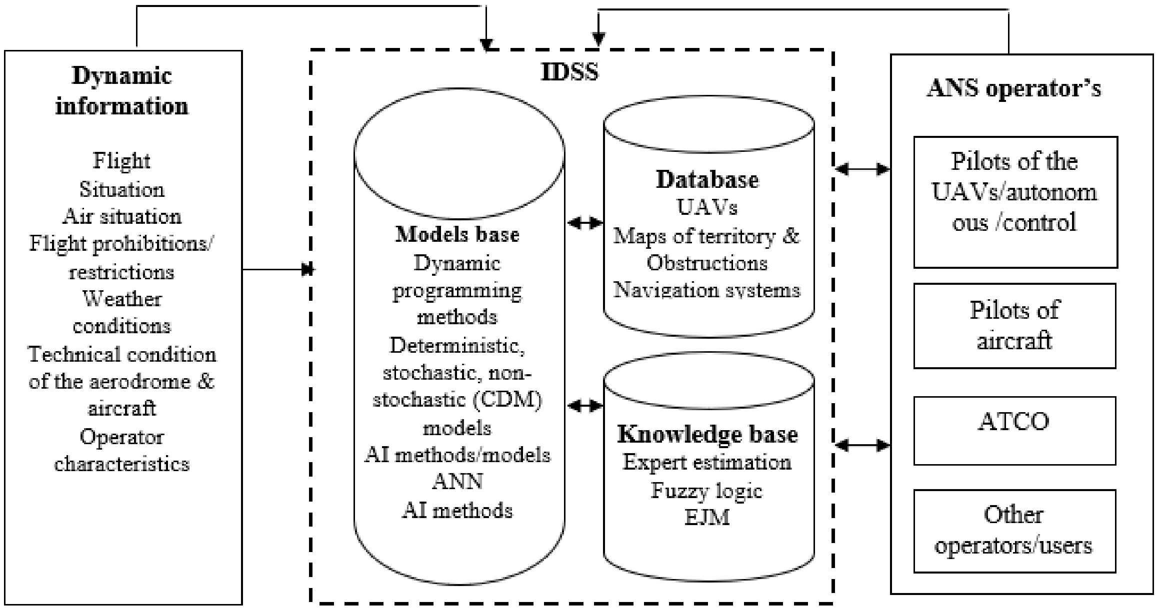

Figure 3: Intelligent control and decision support system for unmanned aerial mobility.

An example of evaluating a fragment of the territory before performing UAV flights around an urban area is shown in Figure 4. The random fragment contains open-air spaces in the form of fields and space with natural obstructions - areas with tall trees, and industrial zone, and an airdrome. There are also high-voltage power lines near the road. To obtain data on the risks a Map of obstructions Google Maps, and Maps.me, Bing, and Google Earth Pro have used. The results of the classification and assessment of the territory of the city fragment are shown in [6]. In the next stage the calculation of the paths with minimum cost for UAVs flights according to specific types of obstructions and minimal risks for flight. Similarly, are performing calculations and obtaining different paths of minimum cost and maximum safety depending on the flight height of UAVs. Calculation of the UAV flight trajectories at other levels of the multi-level airspace is presented in Figure 4.

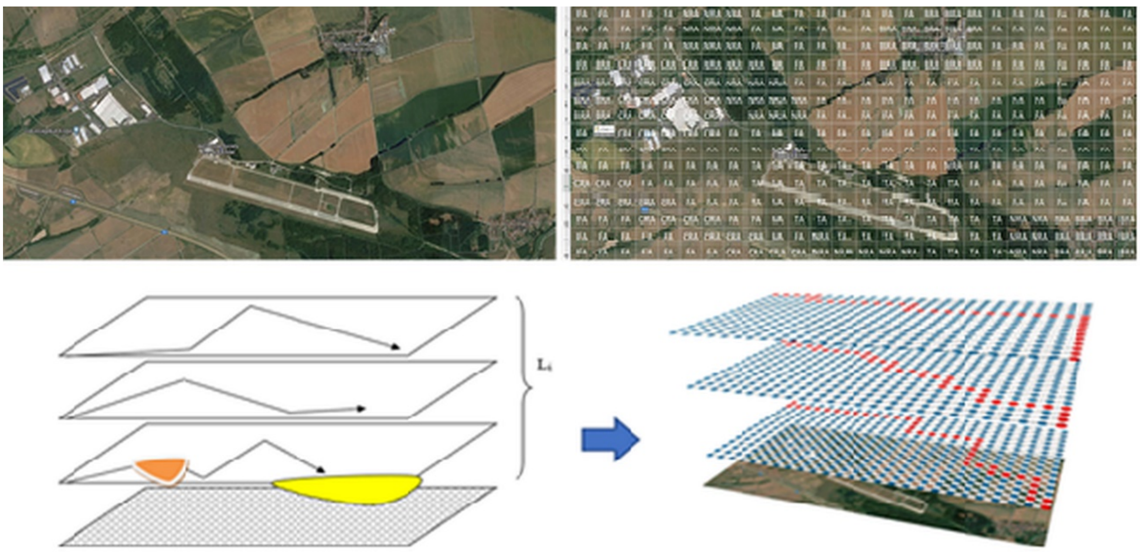

Figure 4: Example of terrain mapping in preparation of autonomous UAV fight

Flight planning of the UAV should be provided for the possibility of performing an emergency landing of the UAV in aerodromes/places/vertiports where the risk to the safety of people, property on the ground, and technical state of UAV and cargo will be minimal and maximal effectiveness of performance of target task [3]. The procedure for the actions of the UAV operators in an emergency is determined in accordance with the Manual on Flight Operations of the relevant UAV. The optimal solutions in emergency landing using the methods of decision-making under uncertainty and risk have been obtained [3]. When analyzing a critical situation in a common airspace, each operator determines its actions for synchronous and balanced problem-solving using CDM models and the subjective-objective method.

2.6. Versatility, Functionality, Security: Protocol Model for Autonomous Aerial Mobility

The vision of efficient and versatile intelligent applications in unmanned aerial mobility, capable of performing diverse complex tasks in a near-autonomous regime depends on developing technologies and protocols that allow simple and efficient integration and management of lower-level functions with well-defined and standard clearly defined interfaces with maximum encapsulation of the internal implementation. This objective can be achieved via introduction of a logical functional framework in the form of a protocol stack model somewhat reminiscent of the OSI (Open Systems Interconnection) model in telecommunications. Unlike the OSI model though, it is rather a logical organization of functions and protocols that support definition and implementation of applications in autonomous unmanned aerial mobility with considerably higher flexibility in the flow of management information and actions between the layers of the model.

The model may comprise the following logical layers:

Physical (P): physical operation of the vehicle. Defines management interfaces to essential functions of the vehicle such as: take-off, landing, movement, power, and other.

Navigation and Communications (N&C): communications protocols and functions for ground control and group communications. Defines management interfaces for communications channels, authorization and authentication, secure communications.

Group operation and management (G): logical protocols for autonomous operation of units in an aerial group.

Functional (F): functions and protocols that are necessary for performing functions and roles specific for certain functional domains, for example: surveillance and search; delivery; scheduled operation, etc.

Application (A): functions and protocols that are necessary for performing application and task-specific functions and roles.

Development of autonomous aerial mobility applications and systems within the framework of the Control of Autonomous Aerial Mobility Protocol Stack (CAMPUS) model would allow:

- A clear separation of functions and utilities between small number of logical management layers
- Encapsulation of functions in the lower level and exposure of clear standard/proprietary management interfaces to simplify the development, targeting, operation and maintenance of UAV systems.
- Standard core control protocol(s) facilitating and ensuring compatibility and inter-operability of UAV management systems, while ensuring uncompromised safety
- Simpler development of complex group and task protocols based on standard-proprietary physical, communications and control layers.
- Eventually, efficient reorientation of a U-team to a different task / area by an update of operation and management software, even dynamically and a few other essential advantages over conventional systems of control and operation of unmanned aerial systems.

3. Conclusion

Development, preparation, organization, management, and execution of safe, coordinated, and effectively integrated functional groups of autonomous mobile aerial units represents a number of essential challenges, of both conceptual and technical nature as has been outlined in this work. Intelligent systems and methods of organization of flight as well as communications and navigation functions are critical for the success of autonomous mobility and the solutions discussed here point a direction for future research in the effective integration of these functions for functionally versatile, essentially autonomous, and safe operation of Unmanned Aerial Systems. A certain limitation of this work, not in the least due to the format, was the scope of the described intelligent models of aerial autonomy, which are many in a domain with the rapidly expanding choice of innovative solutions; nevertheless, it is expected that the principles of integration based on encapsulation and separation of clearly defined standard function discussed here would be fully applicable in those cases as well.

Methods and approaches in Unmanned Aerial Mobility were considered with an emphasis on the organization of safe and efficient UAV flights, especially in critical safety areas such as urban; an architecture of Intelligent Decision Support systems for the human support personnel, operators of UAVs, pilots of aircraft, air traffic controllers, monitor engineers, was proposed, and discussed.

To facilitate the integration of complex and sophisticated functional domains into an effective, functionally versatile, intelligent, autonomous network operating smoothly, flawlessly, and safely a protocol model of Unmanned Aerial Mobility (CAMPUS) is proposed. This approach is innovative in that full interoperability, robustness in operation, and functional versatility is achieved not through complex proprietary implementation but through a model of interconnected standard functions defined in the corresponding protocols. Such a model can be a foundation for the emergence of an ecosystem of intelligent aerial networks and applications performing diverse and critical functions for society. Limitations of the format did not allow for description and discuss the model in more detail that is intended to be a subject of a future study [25].

4. References

[1] V. Gollnick, M.Niklass, M.Swaid, Jan Berling, and N. Dzikus, in: Proceedings of the Aerospace Europe Conference, France, 2020. URL: https://www.academia.edu/66696287.

[2] T. Shmelova, Yu. Sikirda, N. Rizun, and D. Kucherov (Eds.), Cases on Modern Computer Systems in Aviation, IGI Global Publ., Hershey, USA, 2019. doi: 10.4018/978-1-5225-7588-7.

[3] A. Tenedório, R. Estanqueiro, and C. D. Henriques (Eds.), Methods and Applications of Geospatial Technology in Sustainable Urbanism, IGI Global Publ., Hershey, USA, 2021. doi: 10.4018/978-1-7998-2249-3.

[4] D. Bondarev, R.Jafarzadeh, and A.Kozub, Effectiveness of Group Flight of Unmanned Aerial Vehicles, Systems of Information Processing, 6 (122), 2014. URL: https://www.hups.mil.gov.ua/periodic-app/article/11762.

[5] Unmanned Airspace. The information portal for unmanned air system traffic management (UTM), urban air mobility (UAM), counter-UAS (C-UAS), and space traffic management systems, 2021. URL: https://www.unmannedairspace.info./

[6] Unmanned Aircraft Systems Traffic Management (UTM) – A Common Framework with Core Principles for Global Harmonization, 3d ed. Canada, Montreal, ICAO, 2017. URL: https://www.icao.int/safety/UA/Documents/UTM%20Framework%20Edition%203.pdf.

[7] GSMA Smart Cities Guide: Traffic Management, 2016. URL: https://www.gsma.com/iot/resources/gsma-smart-cities-guide-traffic-management/.

[8] Drone life. Urban Air Mobility, 2018. URL: https://dronelife.com/2018/11/28/urban-air-mobility-the-first-uic2-forum-at-amsterdam-drone-week-shows-europes-commitment-to-smart-cities/

[9] Unmanned Aircraft Systems (UAS), Cir. 328/AN 190. Canada, Montreal, ICAO, 2011. URL: https://www.icao.int/meetings/uas/documents/circular%20328_en.pdf.

[10] Manual of Remotely Piloted Aircraft Systems (RPAS), 1st ed., Doc. 10019/AN 507. Canada, Montreal, ICAO, 2015. URL: https://store.icao.int/en/manual-on-remotely-piloted-aircraft-systems-rpas-doc-10019.

[11] Concept of Operations remotely piloted aircraft system (RPAS) concept of operations (CONOPS) for international IFR operations. Canada, Montreal: ICAO, 2017. URL: https://www.icao.int/safety/UA/Documents/ICAO%20RPAS%20Concept%20of%20Operations.pdf.
[12] V. Kuntsevich, Some problems of group motion control of mobile robots. Problems of management and informatics. 1 (2012), 5-18.
[13] Yu. Morozov, Modification and comparative analysis of smooth control laws for a group of agents. Automation and telemechanic. 11 (2012) 96-113.
[14] R. Babaie, A. Ehyaei, Cooperative Control of Multiple quadrotors for Transporting a Common Payload, AUT J. Model. Simul., 50 (2018) 147-156, doi: 10.22060/miscj.2018.14252.5100
[15] J. Jagannath, A. Jagannath, S. Furman, and T. Gwin, Deep Learning and Reinforcement Learning for Autonomous Unmanned Aerial Systems: Roadmap for Theory to Deployment, 2009. URL: https://arxiv.org/abs/2009.03349.
[16] A. Kushleyev, D. Mellinger, C. Powers, and V. Kumar, Towards a swarm of agile micro quadrotors. Autonomos Robot 35 (2013) 287–300. URL: https://doi.org/10.1007/s10514-013-9349-9.
[17] O. Saif, I. Fantoni and A. Zavala-Río, Real-time flocking of multiple-quadrotor system of systems, in: Proceedings of the 10th System of Systems Engineering Conference (SoSE), 2015, 286-291, doi: 10.1109/SYSOSE.2015.7151908.
[18] Q. Zhang, L. Lapierre and X. Xiang, Distributed Control of Coordinated Path Tracking for Networked Nonholonomic Mobile Vehicles, in: Proceedings of the IEEE Transactions on Industrial Informatics, 9 (1), (2013) 472-484, doi: 10.1109/TII.2012.2219541.
[19] O. Mechali, J. Iqbal, X. Xie, L. Xu, and A. Senouci, Robust Finite-Time Trajectory Tracking Control of Quadrotor Aircraft via Terminal Sliding Mode-Based Active Antidisturbance Approach: A PIL Experiment, International Journal of Aerospace Engineering, 2021. URL: https://doi.org/10.1155/2021/5522379.
[20] X.Yu, Ge. Guo and G. Gong, Cooperative control for a platoon of vehicles with leader-following communication strategy, in: Proceedings of the Chinese Automation Congress (CAC), 2017, URL: https://ieeexplore.ieee.org/document/8243988/.
[21] L. Liu, X. Liang, C. Zhu, and L. He, Distributed Cooperative Control for UAV Swarm Formation Reconfiguration Based on Consensus Theory, in: Proceedings of the 2nd International Conference on Robotics and Automation Engineering, (2017) 264 – 268. URL: https://ieeexplore.ieee.org/document/8291392/.
[22] L. Han, X, Cheng, W. Xu, and G. Tan, Reconfigurable Wireless Control System for a Dual-arm Cooperative Robotic System, in: Proceedings of the IEEE International Conference on Robotics and Biomimetics, China, (2017) 202 – 207. URL: https://ieeexplore.ieee.org/document/8324418/.
[23] T. Shmelova, Yu. Sikirda, D. Kucherov, N. Rizun, and K. Dergachov (Eds.), Automated Systems in the Aviation and Aerospace Industries, IGI Global Publ., Hershey, USA. 2019. doi: 10.4018/978-1-5225-7709-6.
[24] F. Govaers (Ed.), Introduction and Implementations of the Kalman Filter, IntechOpen, Fraunhofer Institute for Communication, Information Processing and Ergonomics, Germany, 2019. doi: 10.5772/intechopen.75731
[25] European Union Aviation Safety Agency: Artificial Intelligence Roadmap: A human-centric approach to AI in aviation. Author, Cologne, Germany (2020) URL: https://www.easa.europa.eu/en/document-library/general-publications/easa-artificial-intelligence-roadmap-10