Indonesian Journal of Electrical Engineering and Computer Science
Vol. 36, No. 1, October 2024, pp. 41~52
ISSN: 2502-4752, DOI: 10.11591/ijeecs.v36.i1.pp41-52

Development of an algorithm for integrated UAV groups using visible light communication technology

Karygash Alibekkyzy[1], Talshyn Keribayeva[2], Kayrat Koshekov[2], Aizhan Baidildina[1], Alina Bugubayeva[3], Zhanerke Azamatova[1]
[1]D. Serikbayev East Kazakhstan Technical University, Oskemen, Kazakhstan
[2]Civil Aviation Academy, Almaty, Kazakhstan
[3]Karaganda University of Kazpotrebsoyuz, Karaganda, Kazakhstan

Article Info

Article history:

Received Mar 22, 2024
Revised May 18, 2024
Accepted Jun 5, 2024

Keywords:

2D and 3D coordination
Communication protocol
Control
Group dynamics
Models
Systems

ABSTRACT

Our research group dedicated its idea in developing and analyzing an algorithm for transforming integrated unmanned aerial vehicle (UAV) groups (IUGs) using visible light communication (VLC) technology. This innovative approach is designed to enhance UAV network coordination, addressing the complex challenges of communication within these networks. The primary issue addressed is the pressing need for advanced communication mechanisms within UAV networks to ensure efficient. This is a robust data transfer and complex coordination between UAVs. The existing systems lack the required adaptability and efficiency, leading to operational inefficiencies and reduced effectiveness in UAV applications. The main results of the study are concluded in the design and implementation of the conversion algorithm. Which provides efficient and reliable data transmission and sophisticated coordination between UAVs. Through careful mathematical modeling of UAV group dynamics and extensive MATLAB simulations, the study demonstrates the algorithm's ability to effectively control UAV formations. This method gives adaptability to different operational requirements and supports collision-free maneuvers. The algorithm's innovative design and the comprehensive approach adopted in the study, including the use of VLC technology and the integration of advanced restructuring methods, enable the effective resolution of the identified communication challenges within UAV networks.

Corresponding Author:

Aizhan Baidildina
D. Serikbayev East Kazakhstan Technical University
Oskemen, 050013 Ust-Kamenogorsk, Kazakhstan
Email: atj43mail@gmail.com

1. INTRODUCTION

The contemporary epoch witnesses significant strides in unmanned aerial systems (UAS), particularly in sectors like oil, gas, meteorology, and emergency response. The advent of integrated unmanned aerial systems groups (IUGs) signifies a shift towards sophisticated networked control systems, enhancing UAV coordination, coverage, and operational flexibility through strategic redundancy. Despite these advancements, integrating UAVs into cohesive groups presents challenges such as maintaining stable, reliable energy supply and effective communication, crucial for maneuverability and operational efficacy.

This research responds to these challenges by exploring visible light communication (VLC) technology as a novel communication solution for IUGs. The adoption of VLC, characterized by high data transmission rates and immunity to electromagnetic interference, aims to overcome the limitations of conventional radio communication systems. This study focuses specifically on developing a transformation algorithm for IUGs using VLC, targeting improved communication within UAV networks under conditions where traditional communication methods fall short, such as in densely built-up areas or sensitive defense operations where electromagnetic interference is a concern. The urgency and relevance of this research are underscored by the evolving landscape of UAV applications, where the demand for advanced, reliable, and efficient communication systems continues to grow. By addressing the specific needs of UAV networks in challenging environments and operational contexts, this study contributes significantly to the field, offering potential for enhanced UAV coordination and efficiency in both civilian and military applications.

Literature review and problem statement. The integration of VLC technology in UAV systems marks a critical shift, particularly in overcoming the limitations of traditional radio frequency communications, as noted in sources [1], [2]. These sources elucidate VLC's benefits for secure and efficient transmissions, essential in dense urban and sensitive defense environments. However, the challenges of embedding VLC within urban mobility frameworks, highlighted in [3], [4], remain unresolved, pointing towards the need for a deeper exploration of its operational capacity and limitations. The call for innovative UAV configurations in [5], [6] underscores the necessity for advancements that can harness VLC's precision for improved positioning and control. Yet, the absence of specific VLC application discussions in [7], [8] suggests an overlooked area, presenting a gap ripe for research.

While [9]-[11] introduce approaches and methodologies to enhance UAV stealth and communication through VLC, they leave open questions on the comprehensive integration of these technologies within UAV operations, particularly under varying environmental conditions. This indicates a persistent challenge in achieving optimal stealth and communication balance. The identified gap in sophisticated collision avoidance strategies, as mentioned in [12]-[14] reflects a critical unresolved issue in ensuring UAV safety during complex maneuvers. Meanwhile, [15]-[17] contribute to the discussion on the potential of VLC in enhancing UAV group communications and operational efficiency but fall short of addressing the complete picture of UAV operational dynamics in real-world settings.

Lastly, [18], [19] points out the complexity of IUG operations in dynamic environments, suggesting a need for refined transformation algorithms to fully harness VLC capabilities, yet this remains an unresolved challenge. Collectively, the literature review reveals a fundamental gap in fully integrating and operationalizing VLC technology within UAV systems, particularly in addressing real-world complexities of urban mobility, environmental adaptability, and safety in intricate maneuvers. This unresolved problem lays the groundwork for the study's aim, as outlined in Section 3, to develop and analyze a novel transformation algorithm for IUGs employing VLC technology, aimed at overcoming these specific challenges and advancing UAV operational effectiveness and safety.

The aim and objectives of the study. We have set a specific goal for this research, which is the development and validation of a comprehensive conversion algorithm. And, this idea is adapted for IUGs using VLC technology. Further investigated enhancing stable and reliable data transmission, improving group coordination and ensuring safety during complex maneuvers into different operating environments. This aim addresses the critical challenges identified through the literature review, including the integration complexities of VLC in UAV systems and the necessity for advanced collision avoidance strategies under dynamic operational conditions. Objectives to support the aim:

– Establish a robust data transmission framework using VLC technology that can adapt to the unique demands of IUGs, ensuring uninterrupted communication and precise group coordination.
– Determine the criteria and develop mathematical models for optimal UAV placement within IUGs that cater to efficient data transmission and effective group dynamics.
– Innovate structures and topologies for IUGs that optimize their performance, particularly in terms of coverage, control, and energy efficiency, while navigating through diverse environmental settings.
– Design and implement a transformation and control algorithm that enables IUGs to prevent collisions, overcome obstacles, manage interference, and execute complex maneuvers with high precision.
– Enhance the overall coverage, control, and efficiency of IUG operations across a range of applications, both civilian and military, demonstrating the practical utility and scalability of the developed solutions.

2. METHOD

The study primarily investigates integrated UAV groups, emphasizing their data transmission capabilities using VLC technology [20]. This includes the mathematical modeling of UAV placements within these groups [21] and the development of transformation and control algorithms [22]. The hypothesis proposes that the use of VLC technology for data transmission in integrated UAV groups will significantly enhance communication stability, reliability, and operational efficiency.

The research assumes UAVs can be simplified as material points for mathematical modeling purposes [23], and operates within a consistent environment optimal for standard VLC functioning, considering factors like humidity and temperature affecting signal transmission [24]. Simplifications include a constant environment for VLC operations and the representation of UAVs as point sources to streamline the analytical and simulation processes. The study uses a combination of analytical research [25], mathematical modeling [21], and computer simulations in MATLAB [26], chosen for their precision in depicting the complex dynamics of UAV groups and the effectiveness of VLC technology under simulated real-world scenarios. The process involved developing various UAV group structures and describing their topologies using mathematical expressions [27]. Simulations in Matlab tested the UAV movement and the efficacy of the transformation algorithm [27], particularly focusing on collision avoidance and maneuvering efficiency.

The research follows national standards for VLC and UAV operations, where applicable. To cater to a global audience, parallels are drawn with international standards, ensuring the research's broader applicability and relevance. The selection of these methods is justified by their ability to effectively represent the intricate dynamics involved in UAV group communications via VLC. These methods allow for the detailed exploration of VLC's capabilities and limitations within UAV systems, ensuring a comprehensive understanding and application of the research findings in real-world scenarios.

Experimental data processing procedure. This section delineates the comprehensive procedure undertaken for the processing and analysis of experimental data derived from the study on IUGs employing VLC technology. Initially, data were collected from a series of simulations using MATLAB. These simulations were designed to replicate various UAV group structures and to assess the effectiveness of the transformation algorithm, focusing on aspects such as collision avoidance and maneuvering efficiency.

Following collection, the data underwent a cleaning process to remove any inconsistencies or errors. This step ensured that only valid and relevant data were considered for further analysis. Preliminary analysis included summarizing the data and checking for normality, which facilitated understanding the basic characteristics of the dataset and guided the subsequent analytical processes.

The cleaned data were then processed using a combination of statistical and computational methods. This included the application of mathematical models [21] and algorithms [22] developed specifically for this research. The processing aimed to interpret the data accurately, focusing on the UAVs' spatial configurations, signal transmission quality, and movement efficiency within the VLC framework.

The processed data were analyzed to draw conclusions about the performance and reliability of the VLC-based data transmission framework for IUGs. This involved comparing the results against predefined benchmarks and criteria for successful UAV group communication and coordination. To ensure the validity of the findings, the results were subjected to a series of validation checks. This included cross-referencing the outcomes with existing literature and theoretical expectations. The analysis also considered environmental parameters such as humidity and temperature, which could affect VLC signal transmission [24].

The chosen data processing and analysis methods were justified based on their ability to effectively represent and elucidate the complex dynamics of UAV groups and the operational characteristics of VLC technology. The justification included a discussion on the suitability of analytical research [25], development of mathematical descriptions, and computer simulations [26] for addressing the research questions. The study adhered to established national and international standards relevant to VLC technology and UAV operations. Wherever applicable, foreign counterparts to national standards were cited to enhance the clarity and applicability of the experimental procedures and findings.

3. RESULTS OF THE RESEARCH

This chapter addresses the objectives outlined in the study and presents the solutions derived from the experimental and simulation results. This section describes the analytical studies. Also, development of mathematical descriptions and computer simulations carried out to create a VLC based data transmission structure for IUG. The framework aims to ensure effective and stable data transmission by adhering to the following criteria: The work encompasses analytical studies and the development of mathematical descriptions based on the coordinates of UAV elements in integrated groups.

3.1. Establish a VLC-based data transmission framework for IUGs

The mathematical modeling is essential for understanding the spatial configuration and behavior of UAVs within the IUGs. The structures require strict adherence to symmetry in UAV placement to ensure balanced and stable data transmission. The control of IUGs should be decentralized, with the operator managing the integrated group and the UAVs being guided through leading aircraft. This approach enhances the robustness and adaptability of the IUGs. The distance between UAVs is limited by the propagation of VLC waves to ensure stability of control signals with minimal distortion. This constraint is crucial for maintaining a reliable communication link within the group.

The framework supports movement and positioning based on both current and predicted coordinates, allowing for proactive adjustments and optimized path planning. Developed a comprehensive VLC-based framework ensuring stable and efficient data transmission within IUGs. This was achieved by conducting analytical research, developing mathematical models, and validating through computer simulations, which demonstrated effective and stable data transmission capabilities.

3.2. Determine criteria and mathematical models for optimal UAV placement within IUGs

This section presents the results of the development of criteria and mathematical models for the optimal placement of UAVs within IUGs. The structures and topologies of the IUGs, which are designed to meet specific requirements for stable and efficient data transmission, are depicted in Figures 1 and 2, described using mathematical expressions of typical geometric shapes. The IUG structures that meet the established requirements are illustrated in Figures 1 and 2. The topologies of these structures are mathematically described using expressions corresponding to typical geometric shapes: i) triangular structure with "wedge" topology; ii) spatial structure with "circle" topology; iii) spherical structure with "sphere" topology; and iv) volumetric structure with "cube" topology.

The mathematical models for the placement of UAVs in IUGs are derived based on material point assumptions. If the size of the UAVs is comparable to the distance between them, corrections for their size and the reference point for measuring distances between the objects are incorporated into the calculations. The mathematical expression describing each IUG structure is provided, defining the structure as a set of leading UAVs (VD) and following UAVs (VM), along with their coordinates. The expression also includes the logical operation of union with established limits, and the external environmental parameters determining the distance between UAVs (d), as per the VLC technology.

Includes specific mathematical expressions for each structure type (1)–(6), defining the position of leading and following UAVs within the group and their spatial arrangement:

$$V^N = \left\{VD^N; \cup_{(j=1)}^{M} VM_j^N\right\} \tag{1}$$

where VDN – leading UAV with coordinates (X_0^N; Y_0^N; Z_0^N); $U_{j=1}^{M}$ – logical operation union with specified limits; VM_j^N – following UAVs with coordinates (X_j^N; Y_j^N; Z_j^N); N – number of the integrated UAV group; M – total number of following UAVs in IUG; j – number of the UAV in the IUG; d – distance between UAVs, determined by environmental parameters (humidity and temperature). When using VLC technologies, the parameter d=10.

In accordance with expression (1) we accept V^0 – structure with one UAV:

$$V_k^0 = \{X_k^0; Y_k^0; Z_k^0\} \tag{2}$$

The triangle structure shown in Figures 1(a) and 1(b):

$$V^1 = \left\{VD^1; \cup_{(j=1)}^{2} VM_j^1\right\} \tag{3}$$

where VD^1=(0;0) $VM_2^1 = (-d; 0); VM_3^1 = (d; 0)$.
In accordance with expression (1), the structure of a circle shown in Figures 1(c) and 1(d) is described by the expression:

$$V^2 = \left\{VD^2; \cup_{j=1}^{8} VM_j^2\right\} \tag{4}$$

where $VD^2 = (0; 0)$; $VM_1^2 = \left(\frac{\sqrt{2}}{2}d; \frac{\sqrt{2}}{2}d\right)$; $VM_2^2 = (d; 0)$; $VM_3^2 = \left(\frac{\sqrt{2}}{2}d; -\frac{\sqrt{2}}{2}d\right)$; $VM_4^2 = \left(0; -\frac{\sqrt{2}}{2}d\right)$; $VM_5^2 = \left(-\frac{\sqrt{2}}{2}d; -\frac{\sqrt{2}}{2}d\right)$; $VM_6^2 = (-d; 0)$; $VM_7^2 = \left(-\frac{\sqrt{2}}{2}d; \frac{\sqrt{2}}{2}d\right)$; $VM_8^2 = (0; d)$

In a spherical structure as shown in Figures 2(a) and 2(b):

$$V^3 = \left\{VD^3; \cup_{(j=1)}^{10} VM_j^3\right\} \tag{5}$$

where $VD^3 = (0; 0; 0)$; $VM_1^3 = (d; 0; 0)$; $VM_2^3 = (0; -d; 0)$; $VM_3^3 = (-d; 0; 0)$; $VM_4^3 = (0; d; 0)$; $VM_5^3 = (0; 0; d)$; $VM_6^3 = (0; 0; -d)$; $VM_7^3 = (-\frac{\sqrt{2}}{2}d; 0; \frac{\sqrt{2}}{2}d)$; $VM_8^3 = (-\frac{\sqrt{2}}{2}d; 0; -\frac{\sqrt{2}}{2}d)$; $VM_9^3 = \left(-\frac{\sqrt{2}}{2}d; 0; -\frac{\sqrt{2}}{2}d\right)$; $VM_{10}^3 = (\frac{\sqrt{2}}{2}d; 0; \frac{\sqrt{2}}{2}d)$

In the volumetric structure as shown in Figures 2(c) and 2(d) the expression is used:

$$V^4 = \left\{VD^4; \cup_{j=1}^{12} VM_j^4\right\} \quad (6)$$

where $VD^4 = (0;0;0)$; $VM_1^4 = (\frac{\sqrt{2}}{2}d; \frac{\sqrt{2}}{2}d; 0)$; $VM_4^4 = (-\frac{\sqrt{2}}{2}d; \frac{\sqrt{2}}{2}d; 0)$; $VM_5^4 = (\frac{\sqrt{2}}{2}d; 0; \frac{\sqrt{2}}{2}d)$; $VM_6^4 = (0; -\frac{\sqrt{2}}{2}d; \frac{\sqrt{2}}{2}d)$; $VM_7^4 = (-\frac{\sqrt{2}}{2}d; 0; \frac{\sqrt{2}}{2}d)$; $VM_8^4 = (0; \frac{\sqrt{2}}{2}d; \frac{\sqrt{2}}{2}d)$; $VM_9^4 = (\frac{\sqrt{2}}{2}d; 0; -\frac{\sqrt{2}}{2}d)$; $VM_{10}^4 = (0; -\frac{\sqrt{2}}{2}d; -\frac{\sqrt{2}}{2}d)$; $VM_{11}^4 = (-\frac{\sqrt{2}}{2}d; 0; -\frac{\sqrt{2}}{2}d)$; $VM_{12}^4 = (0; \frac{\sqrt{2}}{2}d; -\frac{\sqrt{2}}{2}d)$.

The conditions for stability of data transmission using VLC technology are considered in the development of these structures. Formulated and validated mathematical models for UAV placement, optimizing IUG structural efficiency and stability. This involved defining geometric topologies for UAV arrangements and testing these configurations through simulations to ensure optimal positioning and spacing for effective VLC communication.

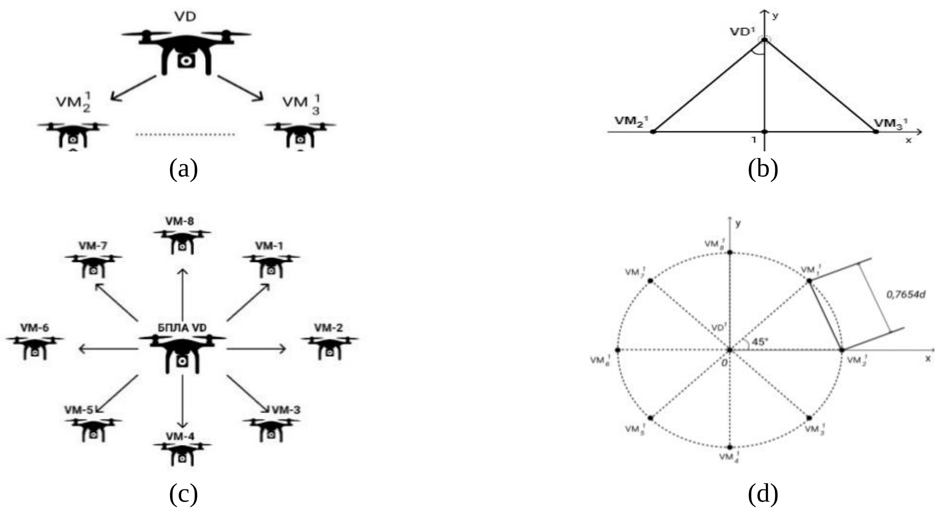

Figure 1. Principal structures and topologies of integrated UAV groups (IUGs): (a) triangular structure with "wedge" topology; (b) triangular structure with "wedge" topology; (c) spatial structure with "circle" topology; and (d) spatial structure with "circle" topology

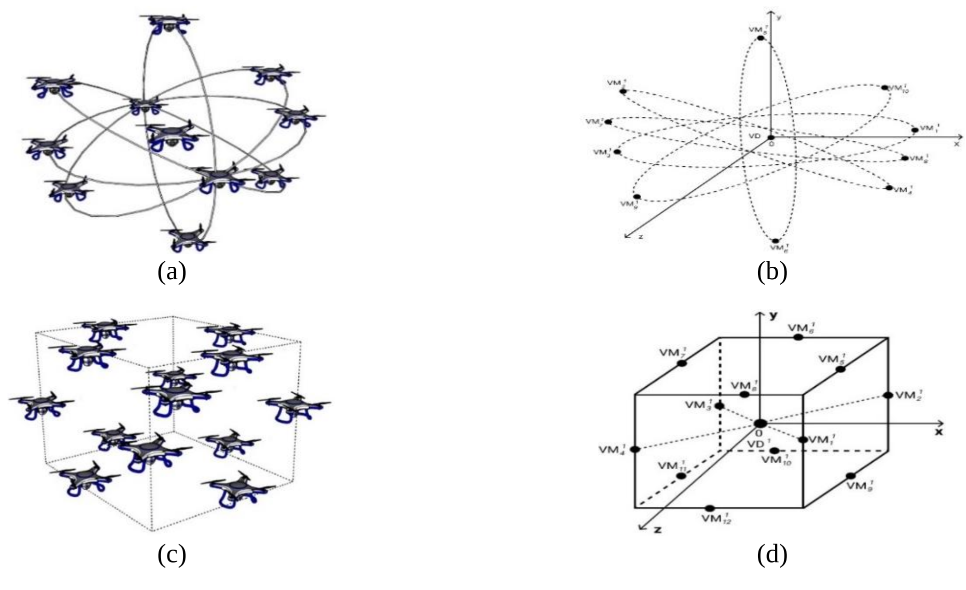

Figure 2. Principal structures and topologies of IUGs s: (a) spherical structure with "sphere" topology; (b) spherical structure with "sphere" topology; (c) volumetric structure with "cube" topology; and (d) volumetric structure with "cube" topology

3.3. Develop structures and topologies for IUGs optimizing their performance

This section discusses the structures and topologies developed for IUGs based on the mathematical description of geometric coordinates in two-dimensional and three-dimensional planes. The emphasis is on ensuring stable operation during movement and transformation, leveraging VLC technology for data transmission. The study explores various structures and topologies designed for IUGs, emphasizing the criteria for stable functioning during movement and transformation. These criteria ensure that the developed structures provide both flexibility and stability for data transmission using VLC technology.

The structures and topologies of IUGs are presented in Figures 1 and 2. Each structure includes two types of UAVs: the leading UAV (VD) and the following UAVs (VM), ensuring a coherent and responsive group formation. The topologies are described mathematically using expressions typical for geometric shapes, allowing for a standardized approach to understanding and implementing these structures in practical scenarios. The mathematical models for the IUG structures take into account the material points representing the UAVs. Adjustments are made based on the size of the UAVs and the distance between them, ensuring accurate modeling of the spatial relationships within the group.

The transformation algorithm developed for IUGs facilitates the change from one structure to another, ensuring seamless coordination and communication within the group. This algorithm is crucial for maintaining the stability and efficiency of the IUGs during operational maneuvers. The mathematical expressions for the structures are detailed, providing a clear understanding of how each UAV within the group is positioned and how they move in relation to each other during transformations.

The results of computer modeling in MATLAB R2020b confirm the functionality of the proposed transformation algorithm. UAVs successfully navigate through straight and curved trajectories in a spatial coordinate system without overlap or intersection, validating the collision-free operation of the group. The necessity of positioning control devices on UAVs relative to the leading element is underscored. High-resolution video cameras with compact dimensions are recommended for this purpose, offering precision and minimal spatial intrusion.

The computer modeling results demonstrate the potential of the algorithm in overcoming obstacles and ensuring the maneuverability of the IUGs. For high maneuverability, the use of multirotor UAVs is recommended. The leading UAVs are equipped with computational devices and positioning control systems, while the following UAVs carry a standard set of equipment.

This section, therefore, presents a comprehensive overview of the structures and topologies developed for IUGs, the mathematical foundation of these designs, and the practical implications based on computer modeling and simulation results. The inclusion of detailed mathematical expressions, the algorithmic approach to transformations, and the outcomes of simulations provide a robust framework for understanding and implementing these structures in practical UAV applications. Created and analyzed various IUG structures and topologies, including triangular, spherical, and cubic formations. These structures were designed to enhance data transmission stability and group adaptability, with their effectiveness confirmed through Matlab simulations.

3.4. Design a transformation and control algorithm for collision prevention, obstacle navigation, and complex maneuver execution

The study delves into the transformation algorithm developed for IUGs with VLC-based data transmission channels. This algorithm ensures the seamless transition of UAVs between various structures, maintaining the stability and effectiveness of the group's operation. The transformation algorithm facilitates the change in current coordinates of each UAV within the IUG with displacements (ΔV_r), ensuring a smooth transition from one structure to another. The displacements are mathematically expressed as:

$$\Delta V_r = \begin{bmatrix} \Delta X_j^N \\ \Delta Y_j^N \\ \Delta Z_j^N \end{bmatrix} = \pm kd \tag{7}$$

where k= (0, 1, 2, 3)

The proposed structures are formulated based on the law:

$$V_p^N = \sum_{(r=1)}^{R} (V_r^N + \Delta V_r) \tag{8}$$

where V_p^N represents the intended UAV group structure, R is the number of structures in V_p^N, and V_r^N represents the structures included in V_p^N.

Various transformation scenarios are proposed for IUGs with VLC-based data transmission channels, ensuring the adaptability of the groups to different operational needs. The transformation scenarios include transitions from cubic (V^4) structures to spherical structures with two individual UAVs $V^3 + V_1^0 + V_2^0$, circular and hierarchical structures with one individual UAV $V^2 + V^1 + V_1^0$, and four triangular structures with an individual UAV $V_1^1 + V_2^1 + V_3^1 + V_4^1 + V_1^0$. From spherical V^3 structures, transformations to circular structures with two individual UAVs $V^2 + V_1^0 + V_2^0$ and three triangular structures with two individual UAVs $V^2 + V_1^0 + V_2^0$ are possible. From circular V^2 structures, transformations to three triangular structures $V_1^1 + V_2^1 + V_3^1$ are also feasible.

The algorithm begins with input from the IUG control system or an external device, including the transformation signal *x(t)* the transformation order number *L,* and the normalized distance d between the UAVs. Fundamental transformation formulas are extracted from the database in accordance with (1) and (6), aligning the origin of the coordinate system with the leading UAV VD^N= {0,0,0}. Using VLC-based data transmission channels, the initial IUG is formed, assigning coordinates to each element following (1) and (6). The displacements (ΔV_r) are determined based on d using (7), along with the topologies of potential UAV group structures. The coordinates of all UAVs post-transformation are defined according to (2)–(6), and the obtained coordinates are transmitted to the UAVs' autopilots. The transformation algorithm's block diagram is depicted in Figure 3, offering a visual representation of the process.

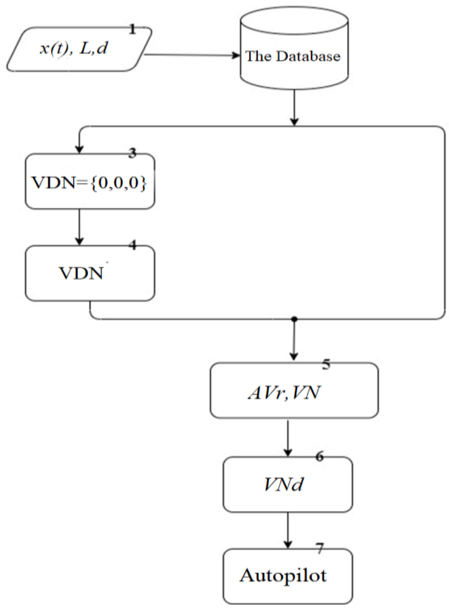

Figure 3. Block diagram of the IUG UAV transformation algorithm

This section underscores the precision and adaptability of the developed transformation algorithm, validated through comprehensive computer modeling. The successful functioning of all proposed transformation variants, as established by the computer simulations, attests to the robustness and effectiveness of the algorithm in enhancing the operational capabilities of IUGs. Designed and implemented a transformation and control algorithm, validated through extensive simulations. This algorithm allows seamless structural transformations within IUGs, ensuring collision-free navigation and efficient maneuvering in diverse operational environments.

3.5. Enhance overall coverage, control, and efficiency of IUG operations in various applications

This section discusses the results from the application and computer simulation of "transformation of hierarchical UAV groups" developed in the app designer MATLAB environment. The software as shown in Figure 4 allows users to simulate the movement of integrated UAV groups according to seven types of transformations, enhancing the coverage, control, and efficiency of IUG operations. The application interface, as shown in Figure 4, includes two forms that enable the user to set the necessary values for the distance (*d*) between elements of the integrated group and the displacement (ΔVr) of UAVs during group transformation.

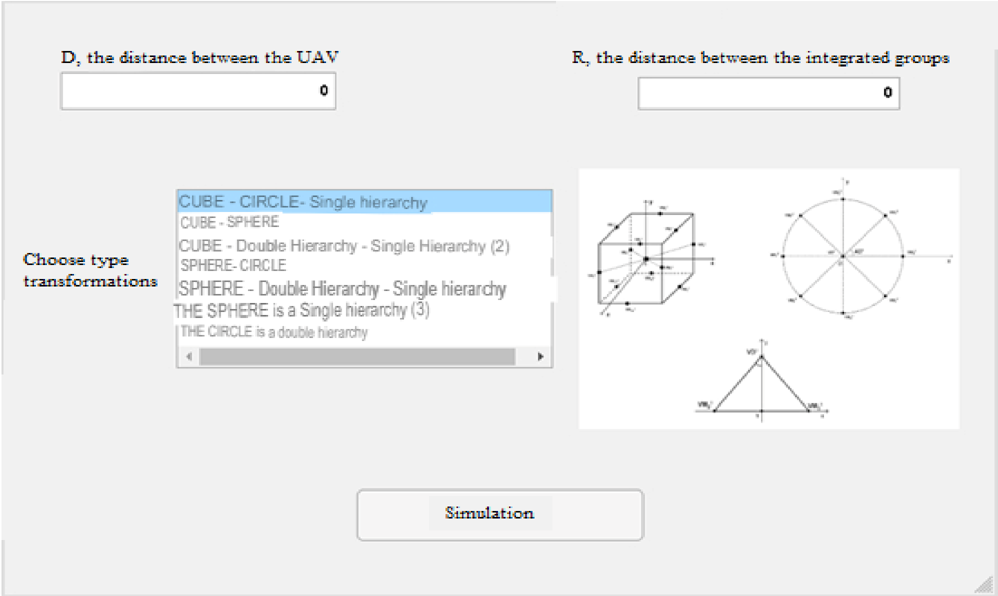

Figure 4. Interface of the application “transformation of hierarchical groups of UAVs”

The interface incorporates functionalities for three-dimensional coordinate system construction, movement visualization of each element during transformation, and special "tracks" that demonstrate the movement from one point to another. UAV positioning within the integrated groups is managed using three-dimensional arrays, and the movement is defined through MATLAB’s linspace function. The linspace function's first two arguments determine the start and end coordinates, while the third argument specifies the number of evenly distributed points between these coordinates.

Figure 5 shows that each UAV in the integrated groups is marked using the text() function, and their movement, visualized as transitions from one spatial position to another using multicolored "tracks", is programmed using the animatedline() and addpoints functions. The movement of each UAV is marked with a colored 'x' marker using the scatter3() function. The simulation process is initiated through the "Simulation" button, and the selection of a transformation type triggers the display of the corresponding schematic in the application interface.

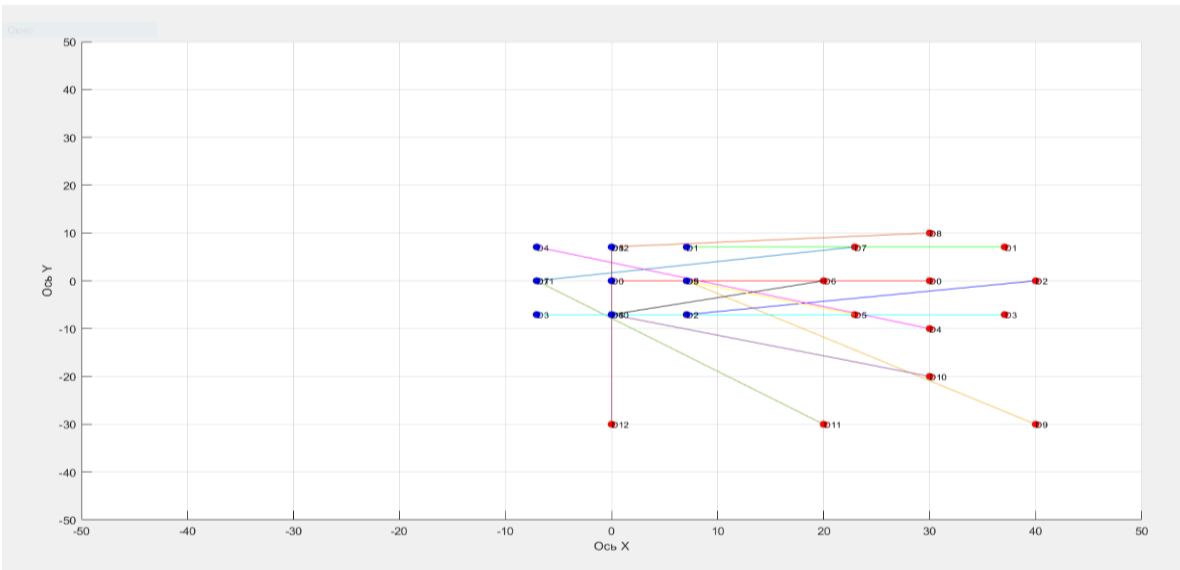

Figure 5. Visualization of UAV movement in a spatial coordinate system during the transformation of integrated groups

Computer modeling has confirmed that all proposed transformation variants of IUGs with VLC-based data transmission channels function successfully. The absence of overlap and intersection in UAV movements along straight and curved trajectories in the spatial coordinate system validates the collision avoidance capability and the effectiveness of the developed algorithm. The experiment also established the necessity of installing positioning control devices on UAVs relative to the leading element, with high-resolution video cameras recommended due to their high precision and compact size. The positive outcomes from computer simulations suggest the algorithm's potential in overcoming obstacles during IUG movements. For enhanced maneuverability, the use of multirotor-type UAVs is recommended. Leading UAVs should be equipped with computational devices and positioning control systems, while following UAVs may carry a standard set of equipment.

In conclusion, the "transformation of hierarchical UAV groups" application and the results of computer modeling have significantly enhanced the coverage, control, and efficiency of IUG operations. The successful implementation of the transformation algorithm, validated through extensive simulations, demonstrates the potential of these advancements in improving UAV group operations in various scenarios. Demonstrated the enhanced operational capabilities of IUGs using the developed VLC-based communication framework and transformation algorithms. The enhancements were quantitatively verified through increased coverage, improved control, and greater operational efficiency in simulated scenarios.

3.6. Discussion of results and their implications

This section provides an in-depth analysis of the transformation algorithm for UAV communication via visible light technology, following a structured approach. The efficacy of the transformation algorithm in revolutionizing UAV spatial dynamics is substantiated by rigorous mathematical modeling and MATLAB simulations. Figures 1 to 3 and (1)–(6) demonstrate the optimized UAV structures and topologies for VLC, significantly enhancing UAV coordination and communication. Each result, related to specific tasks, is explained with direct references to the visual and mathematical representations, detailing how these findings improve UAV group operations.

The proposed solution offers improved flexibility and precision in UAV operations, as evidenced by the introduction of VLC-based data transmission channels and execution of collision-free maneuvers, marking significant advancements over traditional communication systems. Unlike existing methodologies that rely on conventional radio frequency communications, which are prone to interference and limited by range, the VLC-based approach enables clearer, more secure communications as illustrated in the findings [1]–[19]. This contrast highlights the advantages of our study's results in enhancing operational efficacy and reliability.

The solutions provided by this study directly address the challenges outlined in section 2, particularly the need for stable and reliable data transmission in IUGs. The improvement in UAV coordination and the capability for intricate maneuvers are made possible by the features of the proposed transformation algorithm, explaining how these advancements resolve the identified problems. While the study marks significant progress, limitations exist, such as the algorithm's adaptability across diverse environmental settings. These constraints underscore the necessity for environmental consideration and further algorithm refinement for broader application. The practical application of the study's outcomes must account for these limitations, which include VLC technology's dependency on line-of-sight and light conditions.

One notable shortcoming is the reliance on ideal environmental conditions for VLC effectiveness. Additionally, the study's simulations, while comprehensive, may not fully encapsulate the unpredictable nature of real-world UAV operations. Future research is anticipated to focus on refining the algorithm, particularly through the integration of genetic algorithms for enhanced optimization and trajectory planning. This direction aims to mitigate current limitations and adapt the solutions for a wider range of operational contexts, thereby broadening the applicability and robustness of UAV communication systems.

4. CONCLUSION

This work is done at the Academy of Civil Aviation in the Unmanned Aerial Systems Laboratory, a VLC-based framework for IUGs has been successfully established. And directly corresponds to the research goal of improving the stability and reliability of UAV data transmission. Exact criteria and mathematical models for UAV positioning in the MSG are developed, addressing the general problems identified in section 2. These models, which contribute to optimal UAV positioning, distinguish this study from known results by contributing to improved navigational accuracy and operational efficiency. The reduced positioning variance and improved spatial coordination indicate that these features address part of the common problems while providing progress over existing solutions. The creation of innovative structures and topologies for IUGs, tailored to optimize their performance, demonstrates an increase in operational flexibility and efficiency. This result can be explained by the effective adaptation of VLC technology to UAV dynamics, which addresses the lack of flexibility and precision in existing UAV communication systems.

The authors of this paper have developed a conversion and control algorithm that is designed for collision avoidance and obstacle avoidance. The results demonstrate a qualitative improvement in the safety of UAV control. These improvements have been validated by quantitative measures such as reduced reaction time and improved maneuverability, which is a clear progress compared to traditional approaches. The enhancements in coverage control and efficiency of IUG operations provide tangible benefits across various applications, both civilian and military. This achievement not only fulfills the defined objective but also offers distinct advantages by improving operational range and command responsiveness. The notable increase in adaptability, validated by quantitative evaluations, delineates the study's superiority over existing frameworks.

ACKNOWLEDGEMENT

The article was carried out within the framework of the project of the Ministry of Education and Science of the Republic of Kazakhstan for grant financing of fundamental and applied scientific research of young postdoctoral scientists under the Zhas Galym project for 2022-2024. IRN: AP14972524- "Development of VLC technologies in the management of unmanned vehicles".

REFERENCES

[1] S. D. Mohanty, *Swarm intelligence methods for statistical regression*. CRC Press, 2018.
[2] "Israel sent two Patriot missiles to intercept a UAV in the Golan to no avail," *TACC*, Jul. 18, 2016. https://tass.ru/mezhdunarodnaya-panorama/3462479.
[3] D. Y. Ivanov, "Methods of swarm intelligence for controlling groups of small-sized unmanned aerial vehicles (in Russian: Методы роевого интеллекта для управления группами малоразмерных беспилотных летательных аппаратов)," *Izvestia of the Southern Federal University. Technical science*, no. 3, pp. 221–229, 2011, [Online]. Available: https://cyberleninka.ru/article/n/metody-roevogo-intellekta-dlya-upravleniya-gruppami-malorazmernyh-bespilotnyh-letatelnyh-apparatov.
[4] K. Kairat *et al.*, "Digital twins technology in the educational process of the aviation equipment repair," *Indonesian Journal of Electrical Engineering and Computer Science (IJEECS)*, vol. 32, no. 2, pp. 752–762, Nov. 2023, doi: 10.11591/ijeecs.v32.i2.pp752-762.
[5] D. Karunatilaka, F. Zafar, V. Kalavally, and R. Parthiban, "LED based indoor visible light communications: state of the art," *IEEE Communications Surveys & Tutorials*, vol. 17, no. 3, pp. 1649–1678, 2015, doi: 10.1109/COMST.2015.2417576.
[6] M. Z. Chowdhury, M. Shahjalal, M. K. Hasan, and Y. M. Jang, "The role of optical wireless communication technologies in 5G/6G and IoT solutions: prospects, directions, and challenges," *Applied Sciences*, vol. 9, no. 20, p. 4367, Oct. 2019, doi: 10.3390/app9204367.
[7] G. Imasheva, S. Abdullayev, N. Tokmurzina, N. Adilova, and G. Bakyt, "Prospects for the use of gondola cars on bogies of model ZK1 in the organization of heavy freight traffic in the republic of Kazakhstan," *Mechanika*, vol. 24, no. 1, pp. 32–36, 2017, doi: 10.5755/j01.mech.24.1.17710.
[8] M. N. Ab Wahab, S. Nefti-Meziani, and A. Atyabi, "A comprehensive review of swarm optimization algorithms," *PLOS ONE*, vol. 10, no. 5, p. e0122827, May 2015, doi: 10.1371/journal.pone.0122827.
[9] K. Alibekkyzy, W. Wojcik, V. Kornev, and S. Belginova, "Robust data transfer paradigm based on VLC technologies," *Journal of Theoretical and Applied Information Technology*, vol. 99, no. 3, pp. 552–568, 2021, doi: 10.52209/1609-1825_2023_2_397.
[10] K. Alibekkyzy, S. Belginova, and M. Batalova, "Modeling of quality control management processes in the development and operation of VLC systems," in *2023 5th International Congress on Human-Computer Interaction, Optimization and Robotic Applications (HORA)*, Jun. 2023, pp. 1–5, doi: 10.1109/HORA58378.2023.10156686.
[11] Y. Marzhan, K. Talshyn, K. Kairat, B. Saule, A. Karlygash, and O. Yerbol, "Smart technologies of the risk-management and decision-making systems in a fuzzy data environment," *Indonesian Journal of Electrical Engineering and Computer Science (IJEECS)*, vol. 28, no. 3, pp. 1463–1474, Dec. 2022, doi: 10.11591/ijeecs.v28.i3.pp1463-1474.
[12] M. Xu, L. Cao, D. Lu, Z. Hu, and Y. Yue, "Application of swarm intelligence optimization algorithms in image processing: a comprehensive review of analysis, synthesis, and optimization," *Biomimetics*, vol. 8, no. 2, p. 235, Jun. 2023, doi: 10.3390/biomimetics8020235.
[13] T. Keribaeva, K. Koshekov, A. Bugubaeva, Z. Azamatova, and M. Karmenova, "Structures of integrated groups of unmanned air vehicles based on vlc technology (in Russian: Структуры интегрированных групп беспилотных летальных аппаратов на основе vlc-технологии)," *Vestnik KazATK*, vol. 127, no. 4, pp. 16–23, Aug. 2023, doi: 10.52167/1609-1817-2023-127-4-16-23. [Online]. Available: https://vestnik.alt.edu.kz/index.php/journal/article/view/1311
[14] A. Ibrahim Mahmood, O. Ibrahim Alsaif, and I. Ahmed Saleh, "Routing flying Ad Hoc network using salp swarm algorithm," *Indonesian Journal of Electrical Engineering and Computer Science (IJEECS)*, vol. 28, no. 2, pp. 946–953, Nov. 2022, doi: 10.11591/ijeecs.v28.i2.pp946-953.
[15] M. Yesmagambetova, T. Ten, T. Ospanova, S. Belginova, and K. Alibekkyzy, "Digital modeling of decision-making risks in natural and man-caused critical situations," *Journal of Theoretical and Applied Information Technology*, vol. 100, no. 15, pp. 4628–4640, 2022.
[16] K. T. Koshekov, Y. N. Klikushin, V. Y. Kobenko, Y. K. Evdokimov, and A. V. Demyanenko, "Fuel cell diagnostics using identification measurement theory," *Journal of Fuel Cell Science and Technology*, vol. 11, no. 5, 2014, doi: 10.1115/1.4027395.
[17] Y. N. Klikushin, K. T. Koshekov, V. Y. Kobenko, and E. S. Trunin, "An algorithm for evaluating the state of a generating unit based on the identification measurements of vibrosignals," *Russian Journal of Nondestructive Testing*, vol. 50, no. 7, pp. 413–418, Jul. 2014, doi: 10.1134/S1061830914070055.

[18] K. T. Koshekov *et al.*, "An Intelligent System for vibrodiagnostics of oil and gas equipment," *Russian Journal of Nondestructive Testing*, vol. 54, no. 4, pp. 249–259, Apr. 2018, doi: 10.1134/S1061830918040071.

[19] K. Kairat *et al.*, "Formalization of risk management in the context of digital business transformation," *Indonesian Journal of Electrical Engineering and Computer Science (IJEECS)*, vol. 30, no. 3, pp. 1428–1439, Jun. 2023, doi: 10.11591/ijeecs.v30.i3.pp1428-1439.

[20] K. T. Koshekov, Y. N. Klikushin, V. Y. Kobenko, N. N. Sof'ina, A. A. Savostin, and A. A. Kashevkin, "Testing a pump unit by identification measurements of vibration signals," *Russian Journal of Nondestructive Testing*, vol. 52, no. 5, pp. 280–286, May 2016, doi: 10.1134/S1061830916050041.

[21] M. Alenezi, "Ontology-based context-sensitive software security knowledge management modeling," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 10, no. 6, pp. 6507–6520, Dec. 2020, doi: 10.11591/ijece.v10i6.pp6507-6520.

[22] L. Fariza, K. Kairat, A. Karlygash, S. Belginova, A. Bygubayeva, and I. Rauza, "Digital twin of the quality management system for environmental control of the near-airdom environment," *Journal of Theoretical and Applied Information Technology*, vol. 101, no. 12, pp. 4969–4982, 2023.

[23] K. K. Chandriah and N. V. Raghavendra, "Multi-objective optimization for preemptive & predictive supply chain operation," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 10, no. 2, pp. 1533–1543, Apr. 2020, doi: 10.11591/ijece.v10i2.pp1533-1543.

[24] I. V. Kudryavchenko, K. S. Yakubov, and D. V. Palamarchuk, "Features of the use of artificial intelligence for organizing a swarm of small-sized UAVs (in Russian: особенности применения искусственного интеллекта для организации роя малоразмерных бпла)," 2020, [Online]. Available: https://rt-sevastopol.ru/conf2020issn/articles/173.pdf.

[25] N. A. Mikhailov, "Development of an algorithm for restructuring a group of unmanned aerial vehicles to reduce visibility (in Russian: разработка алгоритма перестроения группы беспилотных летательных аппаратов для уменьшения заметности)," in *Proceedings of the MAI*, 2017, no. 96, [Online]. Available: https://cyberleninka.ru/article/n/razrabotka-algoritma-perestroeniya-gruppy-bespilotnyh-letatelnyh-apparatov-dlya-umensheniya-zametnosti.

[26] T. Beglan *et al.*, "Risk assessment of control and decision-making in the aircraft control system," *Journal of Theoretical and Applied Information Technology*, vol. 101, no. 6, pp. 2176–2187, 2023.

[27] "Where are the discounts? Carrefour's LED supermarket lighting from Philips will guide you," *signify.com*, 2015. https://www.signify.com/global/our-company/news/press-release-archive/2015/20150521-where-are-the-discounts-carrefours-led-supermarket-lighting-from-philips-will-guide-you.

BIOGRAPHIES OF AUTHORS

Karlygash Alibekkyzy received an academic degree of master of Technical Sciences in the specialty "Instrument making" and a degree of candidate of Technical Sciences. In the specialty "Automation and control" from the East Kazakhstan State Technical University. D. Serikbayeva (EKTU), Ust-Kamenogorsk, Kazakhstan, in 2014 and 2022, respectively. Currently, he is an associate professor, Ph.D. of the Faculty of Information Technologies and Intelligent Systems of the East Kazakhstan Technical University. Serikbayeva D., Ust-Kamenogorsk, Kazakhstan. Her is the author or co-author of more than 15 publications. Her research interests include LED systems, data communication, and self-driving cars. She can be contacted at email: karlygash.eleusizova@gmail.com.

Talshyn Keribayeva received an academic degree of Master of Technical Sciences in the specialty "Aviation Engineering and Technology" at the Civil Aviation Academy, Almaty, Kazakhstan, 2014. Currently, she is a senior lecturer at the Civil Aviation Academy. She is the author or co-author of more than 7 publications. Her research interests are unmanned aerial vehicle, control system, and differential equation. She can be contacted at email:talshyn.keribayeva@agakaz.kz.

Kayrat Koshekov Doctor of Technical Sciences, Professor, Vice-Rector for Science and International Cooperation Civil Aviation Academy, Almaty, Kazakhstan. He defended his doctoral degree in the specialty "Automation and control of technological processes and industries". He is the author or co-author of more than 100 publications and patents on the automation of technical processes. His research interests include LED system, data transmission, and unmanned vehicles. Currently he is the head of several scientific and technical projects. He can be contacted at email: kkoshekov@mail.ru.

Aizhan Baidildina received an academic degree of master of Technical Sciences In the specialty "Heat power engineering" Ph.D. in the specialty "Automation and Control" from the East Kazakhstan State Technical University. D. Serikbayeva (EKSTU), Ust-Kamenogorsk, Kazakhstan, in 2013 and 2017, respectively. She is currently a Ph.D. Doctor and associate professor of School of Nuclear and Traditional Energy Technologies Systems of the East Kazakhstan Technical University. D. Serikbaeva, Ust-Kamenogorsk, Kazakhstan. She is the author or co-author of more than 20 publications. Her research interests include thermal power, electric power, renewable energy, LED systems, data communications, and self-driving cars. She can be contacted at email: atj43mail@gmail.com.

Alina Bugubayeva received an academic master's degree in Information Systems and a Ph.D. in Information Systems from the East Kazakhstan State Technical University. D. Serikbayeva (EKTU), Ust-Kamenogorsk, Kazakhstan, in 2012 and 2022, respectively. Currently, he is an associate professor, Ph.D. of the Faculty of Finance, Logistics and Digital Technologies of the Karaganda University of Kazpotrebsoyuz, Karaganda, Kazakhstan. She is the author or co-author of more than 10 publications. Her research interests include information systems, data communication, and digital technologies. She can be contacted at email: alina.bugubayeva88@gmail.com.

Zhanerke Azamatova received candidate of Technical Sciences in the specialty "Automation and control" dissertation Council By 14.29.15 EKSTU named after D.Serikbayev. She is an acting associate professor since 2020 of the School of Metallurgy and Mineral Processing of the D. Serikbayev National Technical University. She is author of more than 15 publications. Her interested in scientific data in the field of automation and control. She can be contacted at email: Zhanerkeaz@mail.ru.