



UDC 629.73

IRSTI 50.43.19

[https://doi.org/10.53364/24138614\\_2026\\_40\\_1\\_5](https://doi.org/10.53364/24138614_2026_40_1_5)

**B. Muratkhan<sup>1\*</sup>, A. Koshekov<sup>1</sup>**

<sup>1</sup>Civil Aviation Academy, Almaty, Kazakhstan

\*E-mail: [a.k.koshekov@gmail.com](mailto:a.k.koshekov@gmail.com)

## METHODS OF ANALYZING THE EFFICIENCY AND RISKS OF CONTROL OF UNMANNED SYSTEMS

**Abstract.** *This article examines approaches to improving the reliability and resilience of information exchange for unmanned systems, taking into account the presence of external interference. The primary issue addressed in this article is the analysis of natural and artificial factors that may affect the operation of data transmission channels. Emphasis is also placed on the impact of artificial electromagnetic disturbances. The paper's scientific innovation is that it considers the unmanned system as a multi-agent environment. The agents are the operator, the aircraft, and the external environment. The goal of the study is to improve the reliability of the data exchange channel by implementing Visible Light Communication technology. To achieve this goal, the authors formalized quantitative control assessment methods, developed a structural and functional model of the control system, and conducted simulation tests to assess risks. An analysis of experimental data and computer modeling demonstrated that Visible Light Communication, operating in the infrared range, provides a stable information exchange channel over a distance of up to 3 kilometers. This result demonstrates the potential of using this technology to build a noise-resistant and secure information exchange channel for unmanned systems.*

**Keywords:** *Unmanned aerial vehicle system, Visible Light Communication technology, risk assessment, simulation model, control system model.*

### Introduction.

A systems approach for controlling a dynamic object was first proposed by Russian scientist V. Ivanov [1]. His work proposes integrated interactions within the model using automotive technology as an example. To evaluate the model's effectiveness, the author uses the parameter of traffic safety. Traffic safety is also a key factor in aviation technology.

This study focuses on ensuring the safe operation of a multi-agent UAV system under operator control. Three main actors act as agents in this system. The first is the operator, who is responsible for monitoring the overall situation and making management decisions. The second is the UAV, which is the controlled object and must actively follow the operator's commands, as well as passively respond and report external and internal safety threats. The third is the external environment, which provides data on weather and climate conditions, as well as other risk factors [2].

The "external environment" agent can negatively impact the UAV and create safety risks, while the "operator" agent and its response to changes (threats) influences the consequences of its decisions. Therefore, structuring such risks and their probabilistic quantitative assessment are becoming particularly important. Solving such problems requires the application of formal analytical methods and the use of computer technology [3]. This is because the risks of the

unmanned control process (UCP) compositionally exist as agents of both a material and (virtual) nature. Risks acquire a material socio-economic dimension after the implementation of the adopted decision in practice. This paper proposes combining and quantifying the heterogeneous entities of the system. For example, for digital transformation, several integral "Risk Criteria" (R) are proposed, which correlate with the concept of "Digital Maturity" (DM) [4].

The aim of this work is to improve the operational reliability of the control channel of unmanned systems. To achieve this goal, the authors decided to divide the experimental work into two main stages: systemic and operational. During the systemic stage, control of a multi-agent structure for unmanned systems is implemented. At the operational stage, support is developed for flight missions of unmanned aerial vehicles (UAVs) with manual operator control.

### Materials and methods.

This study aims to investigate the issue of providing a reliable data transmission and reception channel for a UAV control system using Visible Light Communication (VLC). The object of this study is the process of transmitting control commands to the UAV during missions. The subject of the study is to assess the impact of optical conditions and the technical characteristics of the receiving unit on the formation of data transmission errors, the reliability of the communication channel, and risk management.

The method used in this study is based on system analysis, probability and reliability theory, and simulation modeling. In this study, the UAV control system is considered a multi-agent integrated system consisting of the operator, the UAV, and its environment. In the model, the environment acts as a source of disturbances that influences the communication channel and the accuracy of control actions. The purpose of using these methods is to assess the probability of data transmission errors, the reliability of information reception, and the integral risk. To achieve this goal, a simulation model of the VLC control channel for a UAV was developed in Python 3.14.

In the model, we'll define  $X$  as a random value representing the optical state with attenuation and scattering effects. We'll also define  $S$  as the sensitivity of the receiving section. Then, the amplitude of this signal will look like this:

$$A_r = P_t \cdot K_c(X) \cdot S, \quad (1)$$

where  $P_t$  is the optical transmitter power, and  $K_c(X)$  is the transmission coefficient of the communication channel. This coefficient is modeled as follows:

$$K_c(X) = e^{-\alpha(X)L}, \quad (2)$$

where  $\alpha(X)$  is the attenuation coefficient, depending on environmental parameters, and  $L$  is the operating distance. Error in reliable reception  $P$  occurs when the received signal amplitude  $A_{th}$  falls below the threshold  $A_r$ . Therefore, the error probability is determined by the formula  $P_e$ :

$$P_e = P(A_r < A_{th}). \quad (3)$$

During the simulation process, this error is estimated statistically:

$$\hat{P}_e = \frac{N_e}{N}, \quad (4)$$

Where  $N_e$  is the number of erroneous receptions, and  $N$  is the total number of trials. The additional probability in the model is the reliability of information reception and corresponds to:

$$R = 1 - P_e. \quad (5)$$

The reliability of packet data transmission for  $m$  packets is estimated as follows:

$$R_p = (1 - P_e)^m. \quad (6)$$

The assessment of the consequences of signal quality deterioration in the model is introduced through an integral risk indicator. In general, risk is defined as follows:

$$Q = P_e \cdot C, \quad (7)$$

where  $C$  is the error severity coefficient. When considering multiple error factors, the overall risk is calculated as follows:

$$Q_{\Sigma} = \sum_{i=1}^k w_i Q_i. \quad (8)$$

where  $Q_i$  is the partial risk of the  $i$ -th factor and  $w_i$  is the weighting coefficient.

The simulation model operates according to the following sequence of steps: generating environmental and receiving parameters, calculating the attenuation coefficient, determining the signal level, and comparing it with the reference value. A decision is then made on the quality of the receiving signal and statistically evaluating the performance indicators. For example, for the  $j$ -th test, the received signal will look like this:

$$A_{r,j} = P_t \cdot K_c(X_j) \cdot S_j. \quad (9)$$

The model's input parameters include the number of trials, transmitter power, data transmission range, threshold values, attenuation characteristics, environmental distributions, optical sensitivity parameters, and weighting coefficients. The model's output parameters include the estimated error probability  $\hat{P}_e$ , reliability  $R$ , packet transmission reliability  $R_p$ , and overall risk  $Q_{\Sigma}$ . To ensure stable modeling results, the number of trials is matched to the estimated error probability.

The authors' proposed methodology combines the physical characteristics of a VLC channel, environmental effects, and reliability indicators into a single model. This approach is essential for quantitatively assessing communication system performance and control risks. It also allows for the selection of ideal operating conditions for the effective operation of VLC UAV control systems.

#### Results and their discussion.

The structural and functional model of the contextual process of unmanned control (UCC) in the IDEF0 standard is presented in Figure 1. In accordance with this standard, the process (functionality) is represented by a block [5].

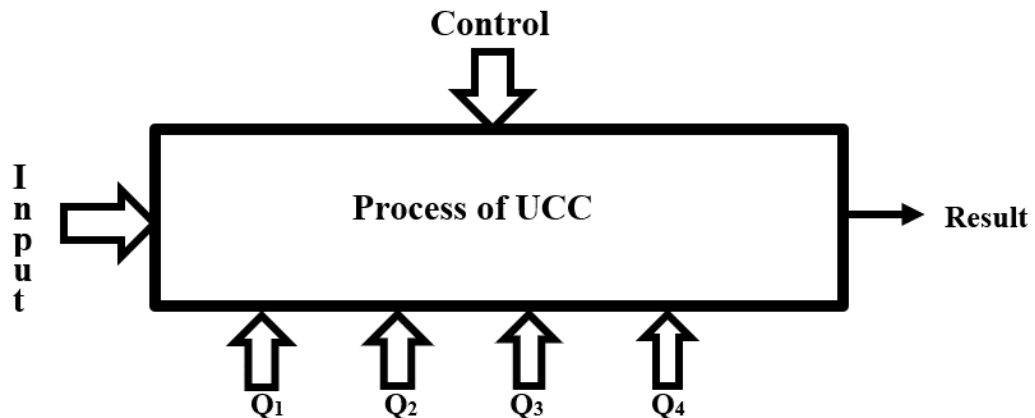


Figure 1 – System model of the unmanned control process (UCC)

In Figure 1:  $Q_1$  – human resources;  $Q_2$  – digital resources;  $Q_3$  – technical resources; and  $Q_4$  – financial resources. In this system model, the performance of an unmanned system is assessed based on risk level  $R_i$ . The operating environment is viewed as cyberspace, in which feedback – "correction" – is a mandatory link. A vector 3D interpretation of the risk management environment is presented in Figure 2. The 3D model provides an integrated visualization of the systemic structural and qualitative composition of risk management agents, which are densely "noisy" with environmental data from passive and active interference.

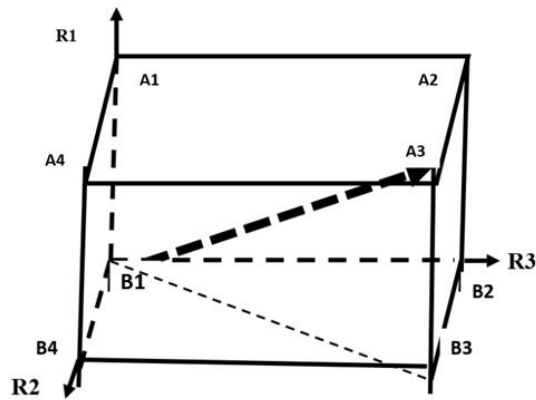


Figure 2 – Virtual composition of a structural 3D model of unmanned aerial vehicle risks

Figure 2 uses the following coordinate vector notations: vector R1 is subjective risk; vector R2 is technical risk; vector R3 is risk due to environmental "noise." Vector B1-A3 is an integrated multifactorial assessment of the unmanned control system. In the systemic structural-functional approach to unmanned control, the vector model is represented by a multi-level and multi-agent cyber-formation. The number of levels and structural agents in systemic inter-agent communications is determined during the research process. Vector B1-A3, in quantitative terms, is hypothetically interpreted by the digital maturity of the system under study or the total risk in unmanned control. Differentiated assessments of the structural systemic components of vectors R1, R2, R3 are in the process of constructing digital twins (DT). The quantitative value of system risks remains to be assessed through further research.

To reduce the impact of interference on UAV control systems, Visible Light Communication (VLC) technology is used in this paper. This technology reduces the impact of external passive atmospheric and active electromagnetic interference [6, 7]. Given these limitations, the VLC information transmission channel is one of the most secure. Another advantage of using this technology is the fact that VLC operates in the infrared range. As noted in the work of R.S. Asatryan, there are "transparency windows" in the infrared region [8]. Due to these windows, the quality of infrared light transmission exceeds that of other known technologies. This is especially critical in foggy or rainy weather. To assess the resilience of unmanned technologies to external influences, the term "susceptibility to interference" is introduced in this paper. A version of the developed structural solution for VLC and information processing is presented in Figure 3.

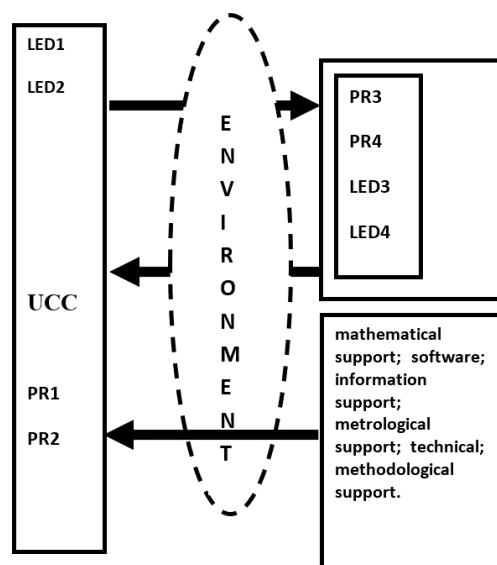


Figure 3 – Structural model of optoelectronic transmission and processing of information

In Figure 3: BPU – control unit of the unmanned optoelectronic system; LED1-LED4 – light-emitting devices; PR1-PR4 – radiation photodetectors.

According to the classification proposed by S. Beer, the system under consideration is highly complex [9]. The system's extreme complexity should be considered not in a static form, but taking into account the feedback loops of system dynamics. The term "system dynamics" was first proposed by Professor D. Forrester; it assumes that processes in technical systems possess stochastic characteristics, a distinctive property being the nonlinearity of processes [10]. As a result, the behavior of such systems defies a strict deterministic description. Complex systems are subject to self-organization, and sudden dynamic phenomena may occur in them. In addition, external influences complicate the process of modeling and forecasting work processes caused by negative influences. To solve such problems, it is necessary to use a differentiated approach, that is, first decomposing the target context and then stepwise analyzing the associated processes. Based on these limitations, the authors proposed a systemic process model for managing unmanned vehicles, taking into account the proposed digital transformation, which is presented in Figure 4.

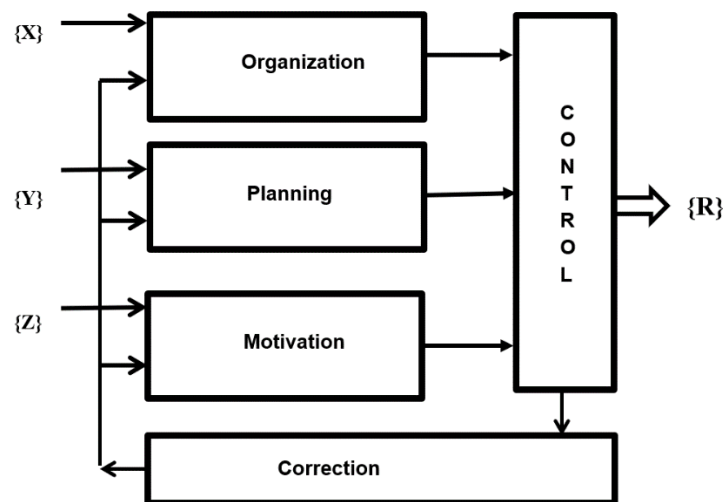


Figure 4 – Decomposition of the contextual process of control of robotic (unmanned) equipment

The primary factor affecting flight safety is the impact of the human factor on risks. To reduce this impact, the use of artificial intelligence technology is proposed, which is particularly important during digital transformation. Despite the advantages of digital technologies, new instrumental risks arise in the system: those related to algorithms, software, and technical infrastructure. These risks primarily arise from the uncertainty of the control process.

In practice, the overall reliability of a system depends on the combined risks of the probabilistic characteristics of its individual elements. These characteristics are often stochastic in nature and directly depend on operating parameters. As a result, quantitative assessment of these parameters is only possible through the use of formal probabilistic methods or simulation modeling. Figure 5 presents an interpretation of the error processes in the VLC systems transmit-receive channel.

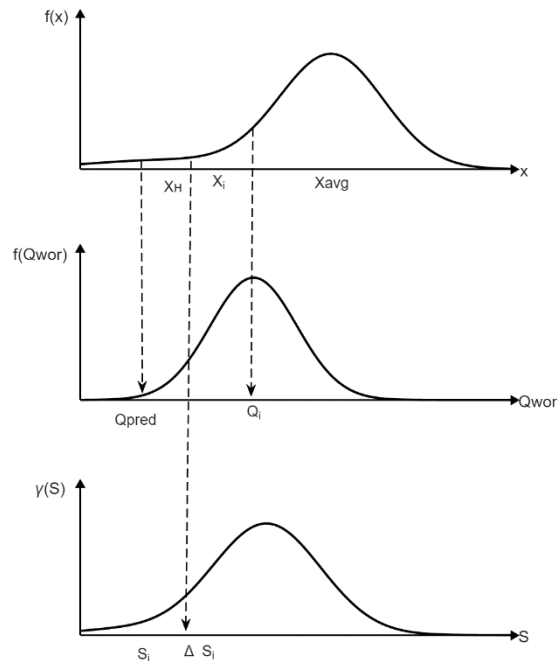


Figure 5 – Schematic diagram of how data transmission and reception errors are generated in the VLC system

The following notations are used in Figure 5:

- $f(x)$  is the density function of the optical density of the external environment;
- $f(q)$  is the density function of the sensitivity of the infrared photodetector;
- $\gamma(S)$  is the density function of the sensitivity of the white light photodetector.

Figure 6 shows a simulation model for studying the performance of a VLC system.

The first block is used to enter the initial data required by the graphical model (Fig. 5) for the simulation algorithm. These data are:  $\sigma_x$  – standard deviation of the optical density-transparency of the environment;  $\sigma_q$  – standard deviation of the sensitivity of the infrared photodetector;  $\sigma_s$  – standard deviation of the sensitivity of the white-light photodetector;  $X_{cp}$  – arithmetic mean of the optical density-transparency of the environment;  $S_{cp}$  – arithmetic mean deviation of the sensitivity of the white-light photodetector;  $Q_{cp}$  – arithmetic mean deviation of the sensitivity of the infrared photodetector;  $N$  – the number of trials (simulations).

The optimal value for the number of trials (iterations),  $N$  is determined during the computer experiment. Sample data during laboratory statistical studies are monitored for homogeneity using standard criteria offered in the Statistica package.

Random number generators are used, as needed, from a list provided in the Python language.

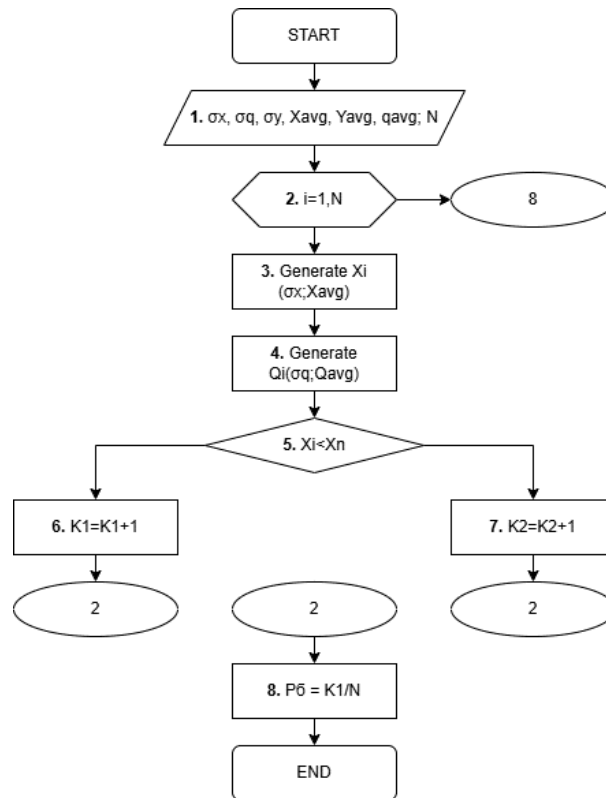


Figure 6 – Simulation model for studying the performance of the VLC system

The quality of information reception and transmission in a VLC channel is affected by a number of artificial and natural factors. Natural factors in this technology primarily include the "optical transparency" of the ambient air. The optical transparency of the ambient air is determined by parameters such as visibility range  $L_M$  is the distance at which a black object can be discerned with the naked eye in daylight.

Table 1 shows the visibility scale (in points), the corresponding  $L_M$  limits, and the volumetric scattering indices  $\sigma_p$ .

Table 1 – Visibility scale, its corresponding limits and volumetric scattering indices

Visibility points	Weather conditions	$L_M$ , km	$\sigma_p$ , $\text{km}^{-1}$
0	Dense fog	<0,05	>78,2
2	Thick fog	0,05-0,2	78,2-19,6
	Normal fog	0,2 - 0,5	19,6-7,82
3	Light fog	0,5-1,0	7,82-3,91
4	Light fog	1-2	3,91 - 1,96
5	Hazy	2-4	1,96 - 0,954
6	Light haze	4 - 10	0,954 - 0,391
7	Clear	10-20	0,391 - 0,196
8	Very clear	20 - 50	0,196 - 0,078
9	Perfectly clear	>50	<0,078
-	Perfect atmosphere	277	0,0141

Therefore, the quality of the environment, in particular the transparency of the atmosphere, must be constantly controlled and monitored. Infrared photodetectors have a specific property - the presence of so-called "transparency windows" in certain frequency ranges. In these ranges, relatively low absorption and scattering of radiation is ensured. In some cases, the infrared receiver

demonstrates acceptable characteristics even in fog and rain, ensuring stable transmission and reception of information at a distance of up to 10 km.

A special device - a driver - is used to control the luminous flux of an LED emitter [9, 10]. The following special types of drivers are offered for high-power LEDs and LED structures: PT4115 (6-30V, 1.2A, 30W, similar to CL6808); CL6708 (6-35V, 1A, 35W); SN3350 (6-40V, 0.7A, 28W); ZXLD1350 (7-30V, 0.35A, 10W); QX5241 (5.5-36V, 2.5A, 40W); AL9910 (15-500V, 40W and more). The wiring diagram for the on-board system's infrared emitter is shown in Figure 7.

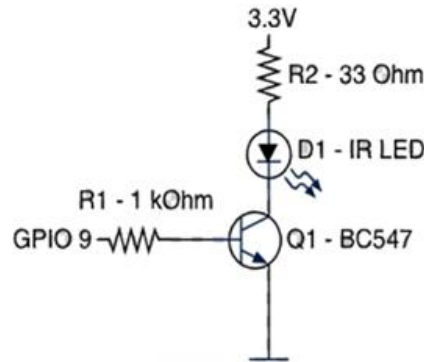


Figure 7 – Wiring diagram of the infrared emitter of the on-board VLC system [10].

To conduct a numerical analysis of the VLC system's operation, the authors developed a virtual model in Python 3.14. This computer experiment was conducted using the laboratory complex of the Civil Aviation Academy. The experiment revealed distribution patterns for each parameter within the model. Key statistical characteristics were also determined, which later formed the basis for the software implementation of the simulation model. Figure 8 shows a histogram of the optical transparency for the VLC system.

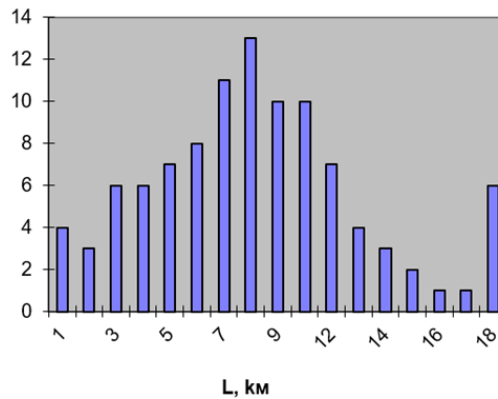


Figure 8 – Histogram of the empirical distribution of the optical visibility of the atmosphere

Based on an analysis of the distribution histogram shown in Figure 8, the authors hypothesized its similarity to the Weibull law. The probability density function of this distribution is as follows:

$$f(L, \alpha, \beta, \gamma) = \frac{\beta}{\alpha} (L - \gamma)^{\beta-1} \cdot e^{-\frac{(L-\gamma)\beta}{\alpha}}, S \geq \gamma. \tag{10}$$

where  $\alpha = 1.0$  is the scale parameter;  $\beta = 3.5$  is the shape parameter;  $\gamma = 1.0$  is the position parameter.

The universality of the Weibull law is ensured by its properties. Reliability theory has shown that the Weibull distribution is used in approximately 60% of practical statistical models.

Furthermore, a number of other distributions can be considered as special or limiting cases of the Weibull distribution. An analytical approximation of empirical data with a theoretical model showed that the hypothesis of a Weibull-like optical transparency distribution is not rejected at a confidence level of 0.95.

A study of the VLC information channel in the visible light range was not conducted within the scope of this work.

### **Conclusions.**

Based on the results of the study, an approach was developed for assessing the reliability of information exchange over a VLC channel for UAV systems. The research methodology involves combining optical channel parameters, environmental characteristics, and signal transmission quality metrics into a single analytical architecture.

The obtained results show that the reliability of a UAV control channel depends on the combined effect of signal attenuation. Reducing optical transparency in the channel or increasing sensitivity increases the probability of an error. This error, in turn, affects reliable signal reception and increases the overall control risk. The results confirm that VLC provides sufficient performance within a certain parameter range.

The scientific contribution of this work to the research area is the development of a simulation model for assessing the reliability of UAV control in the presence of optical interference. Unlike previously considered classical descriptive approaches, the method proposed in this paper quantitatively evaluates reception error, packet transmission reliability, and the integrated risk under various operating conditions. This method provides a basis for comparing channel configurations and determining critical parameter values. The practical significance of the study lies in the model's applicability to the design and testing of UAV communication channels, particularly in environments with electromagnetic interference and enhanced communication security. The model can be used to justify transmitter power selection, determine receiver sensitivity, threshold values, and acceptable maximum operating ranges.

Despite the described advantages, the model has several limitations. The communication process in the study is treated as a simplified probability model, which does not fully account for dynamic processes. Such processes can include UAV maneuvering, complex turbulence, and adaptive modulation and coding mechanisms. Such factors significantly impact channel performance in real-world operating conditions.

Further research will therefore focus on expanding the model to address dynamic operational scenarios, incorporating detailed optical effects, and comparing it with hybrid radio-optical architectures. It is also planned to integrate intelligent algorithms into the model for real-time parameter adjustments to dynamic environmental conditions.

### ***Financing support.***

*This study was carried out within the framework of the program-targeted financing of the Science Committee of the Ministry of Healthcare of the Republic of Kazakhstan, project No. BR28713125 "Development and implementation of unmanned technologies and an intelligent robotic system for pre-flight control to improve safety in air transport."*

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## ҮШҚЫШСЫЗ ЖҮЙЕЛЕРДІ БАСҚАРУДЫҢ ТИІМДІЛІГІ МЕН ТӘУЕКЕЛДЕРІН ТАЛДАУ ӘДІСТЕРІ

*Аңдатпа.* Бұл мақалада сыртқы кедергілердің болуын ескере отырып, пилотсыз жүйелер үшін ақпарат алмасудың сенімділігі мен тұрақтылығын арттыру тәсілдері қарастырылады. Бұл мақалада қарастырылатын негізгі мәселе - деректерді беру арналарының жұмысына әсер етуі мүмкін табиғи және жасанды факторларды талдау. Жасанды электромагниттік кедергілердің әсеріне де баса назар аударылады. Мақаланың ғылыми жаңалығы - пилотсыз жүйені көп агентті орта ретінде қарастырады. Агенттер - оператор, ұшақ және сыртқы орта. Зерттеудің мақсаты - көрінетін жарық байланысы технологиясын енгізу арқылы деректер алмасу арнасының сенімділігін арттыру. Осы мақсатқа жету үшін авторлар сандық бақылауды бағалау әдістерін ресімдеді, басқару жүйесінің құрылымдық және функционалдық моделін жасады және тәуекелдерді бағалау үшін модельдеу сынақтарын жүргізді. Тәжірибелік деректерді талдау және компьютерлік модельдеу инфрақызыл диапазонда жұмыс істейтін көрінетін жарық байланысы 3 шақырымға дейінгі қашықтықта тұрақты ақпарат алмасу арнасын қамтамасыз ететінін көрсетті. Бұл нәтиже пилотсыз жүйелер үшін шуылға төзімді және қауіпсіз ақпарат алмасу арнасын құру үшін осы технологияны пайдалану мүмкіндігін көрсетеді.

*Түйін сөздер:* пилотсыз жүйе, Visible Light Communication технологиясы, тәуекелді бағалау, модельдеу моделі, басқару жүйесінің моделі.

## МЕТОДЫ АНАЛИЗА ЭФФЕКТИВНОСТИ И РИСКОВ УПРАВЛЕНИЯ БЕСПИЛОТНЫМИ СИСТЕМАМИ

*Аннотация.* Статья рассматривает подходы к повышению надежности и устойчивости к обмену информацией для беспилотных систем с учетом наличия внешних помех. Основном вопросом, который решает данная статья является анализ естественных и искусственных факторов, которые могут повлиять на работу каналов

передачи данных. Также упор сделан на анализе влияния искусственных электромагнитных возмущений. В качестве научной новизны в работе беспилотная система рассматривается, как многоагентная среда. В качестве агентов выступают оператор, летательный аппарат и внешняя среда. Целью работы является повышение надежности функционирования канала обмена данными за счет внедрения технологии *Visible Light Communication*. Для достижения данной цели авторами формализованы методы количественной оценки управления, разработана структурно-функциональная модель системы управления и проведены имитационные тесты по оценке рисков. В результате проведенного анализа экспериментальных данных и компьютерного моделирования доказано, что *Visible Light Communication*, работающий в инфракрасном диапазоне обеспечивает устойчивый канал обмена информацией на расстоянии до 3 километров. Подобный результат отражает перспективность использования подобной технологии для построения помехоустойчивого и безопасного канала обмена информацией для беспилотных систем.

**Ключевые слова:** беспилотная система, *Visible Light Communication* технология, оценка риска, имитационная модель, модель системы управления.

#### Information about the authors

Muratkhan Bibigul	Doctoral candidate, Department of Aviation Engineering and Technology, Civil Aviation Academy, Almaty, Kazakhstan, E-mail: Mbibigul1990@gmail.com
Koshekov Abay	PhD, Associate Professor, Department of Aviation Engineering and Technology, Civil Aviation Academy, Almaty, Kazakhstan, E-mail: a.k.koshekov@gmail.com

#### Сведения об авторах

Муратхан Бибиғұл	Докторант кафедр «Авиационная техника и технологии», г. Алматы, Казахстан E-mail: Mbibigul1990@gmail.com
Кошекков Абай	PhD, асс.профессор кафедр «Авиационная техника и технологии», г. Алматы, Казахстан, E-mail: a.k.koshekov@gmail.com

#### Авторлар туралы мәлімет

Мұратхан Бибиғұл	«Авиациялық техника және технологиялар» кафедрасының докторанты, Алматы қ., Қазақстан, E-mail: Mbibigul1990@gmail.com
Көшекков Абай	PhD, «Авиациялық техника және технологиялар» кафедрасының асс. профессоры, Алматы қ., Қазақстан, E-mail: a.k.koshekov@gmail.com