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ARTICLE REVIEW

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IMMERSIVE REMOTE UAV APPLICATION PLATFORM: FACTORS AND REQUIREMENTS

PLATAFORMA DE APLICAÇÃO DE UAV REMOTO IMERSIVA: FATORES E REQUISITOS

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ABSTRACT

Purpose: to substantiate the concept of construction, develop software-algorithmic and hardware solutions that ensure increased accuracy, as well as to study the properties of an on-board navigation complex (OBC) of increased interference immunity based on the remote use of UAVs via a satellite data transmission system (NFRs).

Methodology/approach: The methodological basis and research tool of this study are the methods for building models of dynamic systems, methods of statistical data processing, the theory of optimal evaluation and complex processing of navigation information, methods of simulation and semi-real-life modeling, as well as methods of full-scale testing.

Originality/Relevance: The study conducted a comprehensive analysis of the effectiveness and limitations of the UAV remote control system via a satellite communication channel in the absence of an inertial navigation system (INS). A mathematical model was developed that allows estimating the maximum allowable time for remote use of the UAV without critical loss of controllability.

Key findings: This study lays the foundation for the formation of measurable criteria for the effectiveness of UAV control in conditions of navigation data degradation, with an orientation towards practical implementation in combat, search and rescue or civilian high-risk conditions.

Theoretical/methodological contributions: Systems analysis methods, network interaction theory, mathematical modeling methods, probability theory, machine learning methods, high-level programming theory, software testing methods.

Keywords: Unmanned Aerial Vehicles. Satellite Communication. Signal Delay. Packet Loss. Autonomy. Control Systems. INS-Free Navigation.

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RESUMO

Objetivo: para fundamentar o conceito de construção, desenvolver soluções de software, algoritmos e hardware que garantam maior precisão, bem como estudar as propriedades de um complexo de navegação a bordo (OBC) de maior imunidade a interferências baseado no uso remoto de UAVs por meio de um sistema de transmissão de dados por satélite (NFRs).

Metodologia/abordagem: A base metodológica e a ferramenta de pesquisa deste estudo são os métodos de construção de modelos de sistemas dinâmicos, métodos de processamento estatístico de dados, a teoria de avaliação ótima e processamento complexo de informações de navegação, métodos de simulação e modelagem semi-real, bem como métodos de testes em escala real.

Originalidade/Relevância: O estudo realizou uma análise abrangente da eficácia e das limitações do sistema de controle remoto de VANT via canal de comunicação via satélite na ausência de um sistema de navegação inercial (INS). Foi desenvolvido um modelo matemático que permite estimar o tempo máximo permitido para o uso remoto do VANT sem perda crítica de controlabilidade.

Principais conclusões: Este estudo estabelece a base para a formação de critérios mensuráveis para a eficácia do controle de UAV em condições de degradação de dados de navegação, com orientação para implementação prática em combate, busca e salvamento ou condições civis de alto risco.
Contribuições teóricas/metodológicas: Métodos de análise de sistemas, teoria de interação de redes, métodos de modelagem matemática, teoria da probabilidade, métodos de aprendizado de máquina, teoria de programação de alto nível, métodos de teste de software.

Palavras-chave: Veículos Aéreos Não Tripulados. Comunicação por Satélite. Atraso de Sinal. Perda de Pacotes. Autonomia. Sistemas de Controle. Navegação Livre de INS.

1 INTRODUCTION

Robotic technologies are increasingly used in various types of air, land and sea applications, in the extraction of minerals and the development of natural resources. At the same time, the market for robotic aircraft is developing dynamically. As the total number of unmanned aerial vehicles (UAVs) increases, the problem of their integration into the common space with manned aircraft becomes urgent, the solution of which is possible only when achieving the specified quality of determining the parameters of the UAV movement, including accuracy and noise immunity. Operational standards are being developed by the authorized civil aviation authorities and will probably repeat similar requirements for on-board equipment of civil aircraft. Currently, specialized serial navigation systems for unmanned aircraft, primarily mini-class, that meet the requirements for flight safety in the general airspace, are not offered on the international and domestic markets. The onboard equipment of UAVs is subject to strict requirements for minimizing cost, weight-dimensional characteristics and energy consumption, which are most often mutually contradictory, and their implementation in the general case leads to a deterioration in accuracy and interference immunity. Developers of navigation equipment, UAVs face the problem of ensuring accuracy and interference immunity when using a general-purpose element base. The specifics of using mini UAVs in the absence of ground navigation support in conditions of low-altitude maneuvering flight with reduced visibility and reflection of signals from navigation spacecraft of satellite navigation systems complicates the problem of ensuring accuracy and interference immunity of navigation positioning.

The problem can be solved in two main ways: the first of them is the use of equipment used in manned aviation.

The advantage of this approach is the use of used products and technologies, and the disadvantage is ignoring the specifics of UAVs, which makes it practically impossible to use it as part of a mini-class UAV (Jin, Meng, Dardanelli, Zhu, 2024). Modification of existing navigational onboard equipment of civil aircraft for the needs of unmanned aviation requires significant resources and does not remove a number of fundamental restrictions on application, primarily due to the weight-dimensional characteristics of the equipment and its high cost.

The second way is the creation of specialized navigational complexes of mini-class UAVs, in which low-cost general-purpose equipment should be used. Increasing the accuracy of navigational determination, reliability and unification of methods for designing and testing the hardware and software and algorithmic support of UAV navigational equipment can be achieved through deep integration of systems of different physical nature while maintaining the algorithmic, software and hardware core of the UAV navigation complex based on satellite communication channels, in the absence of an inertial navigation system (INS).

The issue of complex information processing to solve the problems of increasing the accuracy and reliability of navigation systems is revealed in the works (Getting, I. A., 1964), (Parkinson, B. W., & Spilker, J. J., 1996), (Easton, R. L., 1974), (Baumann, W., 1990), (Benedicto, J., Lugert, M., & Gerlach, C., 2013), (Enge, P., & Misra, P., 1994), (Hein, G. W., 2020), (Sermanoukian Molina, I., van den IJssel, J. A. A., Gini, F., & Schoenemann, E., 2024), (Enderle, W., Dilssner, F., Springer, T., Otten, M., Bruni, S., van Kints, M., et al., 2024), (Jin, S., Meng, X., Dardanelli, G., & Zhu, Y.,2024).

The problem of improving the quality of transmission in UAV networks was solved by the laboratories of Communication System and Networks (Tampere), Lakeside Labs GmbH (Klagenfurt), EPFL (Lausanne), and Universität Bern (Bern).

The current problem of ensuring the interference immunity of navigation equipment can be solved on the basis of building algorithms for complex information processing with a variable structure, which allows to estimate the errors of each subsystem and implement algorithms for detecting and eliminating failures of various types.

The **purpose** of the work is to substantiate the concept of construction, develop software-algorithmic and hardware solutions that ensure increased accuracy, as well as to study the properties of an on-board navigation complex (OBC) of increased interference immunity based on the remote use of UAVs via a satellite data transmission system (NFRs).

The **object** of the research is a UAV with the possibility of remote use using a satellite data transmission system (NFRs) of a mini-class fixed-wing, designed to solve a wide range of practical tasks.

The **subject** of the research is the algorithmic support of the UAV, which includes procedures for complex processing of variable structure information, which provide increased immunity to interference due to remote use using a satellite data transmission system (NFRs).

2 THEORETICAL REFERENCE

2.1 Contradiction

The use of mini unmanned aerial vehicles (UAVs) in various fields of activity is becoming more and more widespread every year. The greatest potential for their use lies, according to the authors, in flights beyond the direct line of sight in remote mode.

By remote mode, we mean the movement of the UAV with the remote presence (control) of the operator (pilot), without the use of an inertial navigation system and GPS or its analogues, but with occasional inclusion at the beginning of the UAV flight trajectory.

However, the use of the UAV in this mode of operation imposes strict requirements on navigation characteristics.

The accuracy of the initial positioning of the UAV navigation equipment and means is the most important characteristic that determines the quality and possibility of performing the flight task and depends on many factors (Enderle, W., Dilssner, F., Springer, T., Otten, M., Bruni, S., van Kints, M., et al., 2024).

The basis of the UAV control method is the use of satellite navigation systems (SNS), the main of which is the GPS system and its functional additions. However, when the navigation field is distorted, significant positioning errors (interference) may occur, which complicates or makes it impossible to use the UAV in unstable electromagnetic conditions.

Aircraft are forced to interrupt the flight and perform an emergency landing. Most often, in such conditions, the UAV crashes.

The navigation field created by satellite navigation systems is subject to unintentional distortion by man-made structures, terrain, communication means with high radiation power, which significantly exceeds the navigation field created by satellite navigation systems, as well as intentional influence by special electromagnetic devices for capturing UAV control or temporary suppression of the signal of satellite navigation systems (Hein, G.W., 2020).

The magnitude of the distortion of the navigation field can vary widely along the flight path. The most significant natural source of positioning errors is ionospheric signal distortion.

Existing methods for determining the states of the satellite radio navigation signal propagation path are usually based on predictive models (Ahmed, M., Nasir, A. A., Masood, M., Memon, K. A., Qureshi, K. K., Khan, F., Han, Z., 2025). However, predictive models do not allow for the full impact of small-scale ionospheric inhomogeneities to be taken into account and provide only approximate values for changes in parameters that determine the state of the satellite radio navigation signal propagation path.

The widely used methods for increasing the positioning accuracy of UAVs are based on the use of the GPS differential correction system, have a small effective radius of use (up to 25 km) and require an additional communication channel with the operator's (pilot's) navigation equipment (Sermanoukian Molina, I., van den IJssel, J.A.A., Gini, F., & Schoenemann, E., 2024), (Novák, A., Kováčiková, K., Kandera, B., & Sedláčková, A. N. (2024). In this case, to ensure the mobility of the operator (pilot), it is necessary to build a distributed network of base stations, which is economically impractical. The contradiction in practice is that existing practical solutions used to increase the positioning accuracy of UAVs in remote flight mode do not provide the necessary positioning accuracy when the navigation field is distorted/suppressed. Limitations on weight-and-dimensions of mini UAVs do not allow the use of more high-precision and additional equipment that provides better characteristics and accuracy of UAV positioning.

The contradiction in theory is that existing theoretical approaches allow for an acceptable error in the navigation position of UAVs in remote flight mode. To resolve this contradiction, it is necessary to develop a new scientific and methodological apparatus, namely, methods, models and methods that allow for increasing the accuracy of mini UAV positioning in conditions of distortion/suppression of the GPS navigation field or its analogues, to perform special tasks.

2.2 Non-functional requirements for a UAV control system via satellite data transmission system (NFRs)

1. Latency

Average signal delay ≤ 100 ms between command transmission from base and UAV response. In critical scenarios, a peak delay of up to 150 ms is allowed in no more than 5% of cases.

2. Link Availability

The satellite data transmission system communication channel availability must be at least 99.5% throughout the mission. The system must have a mechanism to automatically switch to an alternative channel (e.g. LTE/4G) in the event of a loss of satellite communication for 2 seconds.

3. Packet Loss

Packet loss monitoring should be available in real-time via the control panel.

No more than 50 lost packets per 1000 packets transmitted (i.e. ≤5%), provided buffering and error correction are in place.

4. Performance

The bandwidth of the communication channel must ensure the transmission of data, video (720p) and control commands in real time - at least 5 Mbps in the uplink direction and 10 Mbps in the downlink.

5. Security

Authentication of users of the control system shall be carried out through two-factor authentication.

Protection against unauthorized access to the satellite data transmission system terminal shall comply with NIST/ENISA requirements.

6. Reliability & Fault Tolerance

The probability of complete loss of control of the UAV should not exceed 0.1%.

7. Scalability

Ability to integrate with other types of communication channels (e.g., LoRa, LTE, RF) without modifying the system core.

8. Usability

The pilot-operator interface must be intuitive and adapted for field operation (low light mode).

9. Portability & Power

All elements (satellite data transmission system terminal, controller, monitor) must be powered by an autonomous power source (battery, powerbank) with a total duration of autonomous operation of at least 3 hours. The weight and dimensions of the complex must allow its mobile movement.

Taking into account the above requirements, we will determine the maximum operation time without loss of controllability of a multirotor type UAV in flight mode (without GPS) under conditions of distortion/suppression of the GPS navigation field.

The remote flight time under conditions of distortion/suppression of the GPS navigation field is determined from the equation based on the express error estimation formula. Additionally, the coefficient α is introduced to reduce packet losses to an equivalent time effect, since the loss of one packet delays or distorts the transmitted command.

Adapted formula for UAV control system via satellite information transmission system to determine maximum operation time without loss of controllability $t_{\max remote}$, looks like:

$$t_{\max remote} \le \frac{2500 \times T_c^{\Delta\omega} \times \left(\Delta_{\sigma_k}\right)^2}{g^2 \times \left(\tau_{delay} + \alpha \times PLR\right)^2}, \quad (1)$$

where

$T_c^{\Delta\omega}$ - update step taking into account rotation dynamics;

Δ_{σ_k} - permissible deviation (system accuracy);

α - empirical coefficient for converting packet losses into control time failures (may be ≈ 0.01–0.05 depending on the system);

$\alpha \times PLR$ - the impact of packet loss on loss of controllability is given;

τ_{delay} - fixed/floating signal delay;

g - 9.81 m/s².

The physical meaning of the expression is that the greater the transmission delay, packet loss, the less time the system can remain stable without updating or correction. The numerator reflects the permissible deviations and rotation speed. The denominator takes into account the influence of communication delay and packet loss, as the main sources of error in remote control.

The expression takes into account the real risks of satellite communication - delays, losses and allows you to estimate the maximum operation time without loss of controllability. It is universal - it can be adapted to other types of channels, such as LTE, radio or Wi-Fi. According to the obtained expression, mathematical modeling was carried out and a graph was constructed of the dependence of the maximum time of remote operation of the UAV on the communication delay for different levels of packet loss (PLR) (Figure 1).

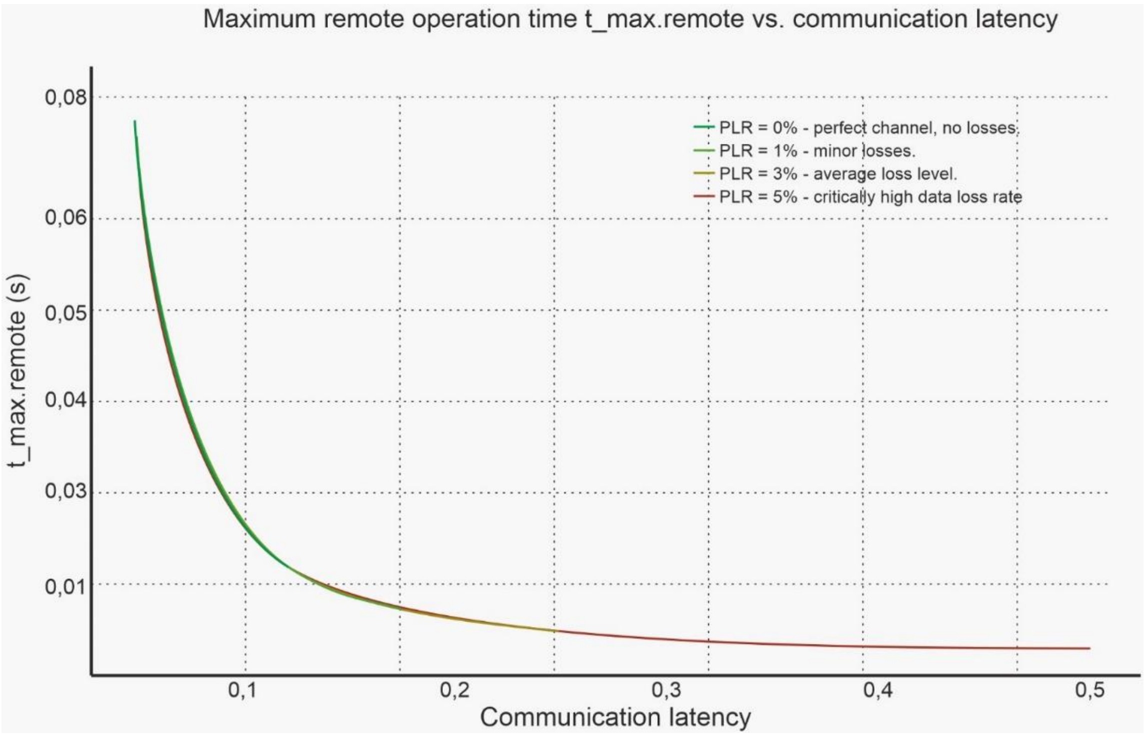

Figura 1. Graph of the maximum UAV remote action time versus communication delay for different packet loss levels (PLR)
Source: Authors

The graph shows that the higher the latency, the less time the system can operate without a critical loss of control. Even 1–3% packet loss has a significant impact on reducing the safe uptime. In the case of latency of 300+ ms and PLR > 3%, the uptime drops to 1–3 ms, which effectively means uncontrollability.

3 METHOD

Experimental project methodology

1. Purpose of the experiment

To determine the maximum autonomous operation time of a mini-UAV in remote control mode via a satellite data transmission system without INS and taking into account obstacles in the navigation field (GPS distortion, packet loss, transmission delay).

2. Selection criteria

- Latency: 50 to 400 ms (based on real Starlink and satellite channel characteristics).
- PLR: 0 to 5% (realistic high-obstacle conditions).
- Initial accuracy: ±1–5 m (typical mini-UAV characteristics).
- Angular velocity: based on the maneuvering characteristics of a specific UAV.

3. Justification of the use of software and models

UAV mathematical model:

- Adapted formula for express estimation of autonomy time without loss of controllability.
- INS parameters replaced by characteristics of the communication channel (delay, PLR).

Software:

- MATLAB/Simulink or Python (NumPy, SciPy, Matplotlib) for:
- numerical simulation of UAV dynamics;
- plotting graphs of autonomy time versus delay and PLR;
- conducting Monte Carlo simulations to assess the variability of results.

Justification:

The software allows you to implement complex system dynamics and take into account random packet loss, delay, and positioning errors.

4. Research limitations

The model does not fully account for external environmental factors (wind, turbulence, weather conditions).

Simplified UAV dynamics are used without full modeling of all physical forces.

Limited accuracy of delay and packet loss prediction in real satellite networks.

The modeling is focused on mini- and medium-sized UAVs, and does not take into account large platforms with additional sensors.

5. Reproducibility of results

Use of uniform model and software parameters.
Saving input data for simulations: latency, PLR, initial positions.
Providing MATLAB/Python scripts for reproducing results and plotting graphs.
Description of the procedure for simulation series and Monte Carlo iterations.

6. Metrics for assessing reliability and validity

Tmax – maximum autonomy time without loss of controllability.

Sensitivity of the system to latency and PLR (defined as the derivative of Tmax with respect to the variable).

Probability of complete loss of controllability at given parameters (Reliability ≤0.1%).

Standard deviation of Tmax in Monte Carlo simulations → assessment of model stability.

Coefficient α for converting packet losses into equivalent loss of controllability time.

4 DISCUSSIONS

The study conducted a comprehensive analysis of the effectiveness and limitations of the UAV remote control system via a satellite communication channel in the absence of an inertial navigation system (INS). A mathematical model was developed that allows estimating the maximum allowable time for remote use of the UAV without critical loss of controllability, taking into account the key characteristics of the data transmission channel - in particular, signal delay (latency) and packet loss rate (PLR).

The adapted formula replaced the inertial error parameters (gyroscope noise) with the communication characteristic, which allowed us to quantitatively assess the impact of adverse data transmission conditions on mission effectiveness.

Analytical and graphical results showed that:

the system's sensitivity to delay increases quadratically: an increase in latency even by 100–200 ms sharply reduces the safe autonomous operation time;

PLR at the level of 3–5% with a typical Starlink delay (200–300 ms) leads to a reduction in the allowable autonomous time to critical values of less than 5–10 ms, which makes real-time control practically impossible;

the calculated critical limit of PLR at a delay of 200 ms turned out to be theoretically negative, which indicates the actual unsuitability of such a configuration for stable remote control without additional stabilization means or local decision-making.

In view of this, a set of non-functional requirements (NFRs) was formulated for such systems, which include: an allowable delay level (up to 150 ms), a maximum packet loss threshold (no more than 1–2%), mandatory support for an emergency algorithm (RTB, hover, loiter), the use of QoS control at the network level, as well as channel security and redundancy.

Table 1. UAV Remote Control: Key Findings and Recommendations under Interference Conditions

Section	Content
1. Impact of Interference on UAV Navigation (Scientific Findings)	Latency and packet loss (PLR) are critical for safe UAV operation in BVLOS mode without an INS.- System sensitivity to delay increases quadratically; even small packet losses (3–5%) at typical satellite channel delays dramatically reduce allowable autonomy time. The adapted express formula for estimating Tmax allows quantitative assessment of the impact of adverse communication channel conditions on controllability. Introduction of the α coefficient to account for packet loss integrates communication characteristics into flight safety assessment. A standardized approach for estimating Tmax under different latency and PLR conditions has been developed. Provides a basis for reproducible simulation studies using MATLAB/Python and Monte Carlo methods.
2. Practical Implications	For UAV engineers and developers: integration of local navigation algorithms and autonomous solutions to compensate for unstable channels; development of software with limitations on acceptable autonomy time, latency, and packet loss. For operators and pilots: implementation of autonomous obstacle avoidance modes, transition to standard mission, and emergency algorithms (RTB, hover, loiter). For defense and rescue services: use of mini-UAVs in high-risk scenarios (EW, GPS jamming, weak signal); mission planning considering critical Tmax limitations to ensure flight safety.
3. Application Scenarios	**Military missions:** reconnaissance flights, operations under electronic suppression conditions. **Search and rescue operations:** BVLOS in hard-to-reach areas in the absence of GPS. **Environmental monitoring:** surveillance of large areas, especially in remote or high-risk zones.
4. Future Research Directions	**Integration with AI systems:** using ML/AI for autonomous real-time decision-making. **Hybrid inertial systems (INS):** combining simplified INS/DR with satellite channels to improve positioning accuracy. **Extension to medium-sized UAVs:** adapting methods and models for platforms with higher payload and energy resources.
5. Increasing the Added Value of Research	Ensuring sustainable competitive advantage through: innovative approaches to autonomous control; enhancing UAV safety and reliability; optimizing operational efficiency in challenging conditions. Results can serve as a basis for standardizing UAV control systems and implementing cutting-edge technologies in both civil and defense sectors.

The table summarizes the critical insights from the study on UAV remote control via satellite communication under interference conditions. Scientific findings highlight the impact of latency and packet loss on flight safety and controllability, while practical implications provide guidance for engineers, operators, and defense or rescue services. Application scenarios demonstrate the versatility of UAVs in military, search and rescue, and environmental monitoring missions. Future research directions focus on AI integration, hybrid inertial navigation, and adaptation to medium-sized UAVs. Overall, the study offers a structured framework to enhance UAV autonomy, safety, and operational efficiency, providing a foundation for standardization and technological innovation in both civil and defense sectors.

Recommendations

1. Integration with broader societal and organizational applications. Enhancements in UAV control systems and navigation resilience should not be limited to military or high-risk missions. Their application can be extended to logistics (last-mile delivery, cargo monitoring), agriculture (precision farming, crop health analysis), smart city monitoring (infrastructure inspection, traffic and air quality monitoring), and environmental sustainability (climate observation, biodiversity tracking). Linking UAV technological improvements with these domains strengthens the societal impact and facilitates dual-use innovation.
2. Competitive advantage through increased reliability. Improved UAV reliability under conditions of interference and degraded navigation ensures operational continuity and reduced mission failure risks. For companies, this translates into cost savings, trust from clients, and the ability to expand into high-risk or hard-to-reach markets. For public institutions and defense/rescue agencies, reliable UAV systems provide strategic resilience, enhanced national security, and greater public safety outcomes.

Thus, increasing UAV system robustness is not only a technical objective but also a source of long-term competitive advantage in both the civil and defense sectors.

Linking Research Results with the UN Sustainable Development Goals (SDGs)

1. SDG 9: Industry, Innovation and Infrastructure
Research in the field of unmanned aerial vehicles (UAVs) contributes to the advancement of innovative technologies for monitoring, logistics, and security. The development of resilient control solutions for UAVs under conditions of electronic warfare strengthens scientific and technological capacity and supports the creation of innovative infrastructure.
2. SDG 11: Sustainable Cities and Communities
The application of UAVs in civil security, environmental monitoring, and infrastructure inspection enhances the safety and resilience of cities. These technologies can be employed in emergency response, search and rescue operations, and disaster management, directly contributing to safer and more sustainable communities.
3. SDG 13: Climate Action
UAVs play an important role in monitoring climate change, soil quality, water resources, and forest ecosystems. The results of such research provide accurate data that support climate adaptation strategies, help optimize resource use, reduce emissions, and foster sustainable development in the face of environmental challenges.

The conducted research demonstrates that advancing UAV technologies is not only a matter of improving operational reliability and resilience in complex environments but also a significant contribution to broader societal goals. By linking the outcomes with the UN Sustainable Development Goals, this study highlights how UAV innovation strengthens industry and infrastructure (SDG 9), supports the development of safer and more sustainable communities (SDG 11), and provides essential tools for climate monitoring and action (SDG 13). In this way, UAV research generates both scientific value and tangible benefits for global sustainability, security, and technological progress.

5 FINAL CONSIDERATIONS

Practical recommendations:

In conditions of performing special tasks or the absence of GPS, the integration of edge navigation algorithms and local decision-making (based on machine learning models or simplified INS/DR) becomes critical.

High-frequency packet loss and unstable latency require dynamic redistribution of responsibility between the operator and the UAV - in particular, the introduction of modes with autonomous obstacle avoidance or transition to the default mission.

The proposed formula can be used to construct constraints in the UAV control system software or as part of the communication channel reliability standards in conditions of interference (EW, weak signal, deliberate attack on infrastructure).

The practical value of the research results is determined by the developed schemes, mathematical models, algorithms, and hardware solutions that can be used by developers and manufacturers of onboard navigation systems for small and medium-sized UAVs.

Thus, this study lays the foundation for the formation of measurable criteria for the effectiveness of UAV control in conditions of navigation data degradation, with an orientation towards practical implementation in combat, search and rescue or civilian high-risk conditions.

REFERENCES

Ahmed, M., Nasir, A. A., Masood, M., Memon, K. A., Qureshi, K. K., Khan, F., & Han, Z. (2025). Advancements in UAV based integrated sensing and communication: A comprehensive survey. *IEEE Communications Surveys & Tutorials*. Advance online publication. Retrieved from https://ieeexplore.ieee.org/document/10778981

APNIC Blog. (2024, April 19). A multifaceted look at Starlink performance: The good, the bad and the ugly. *APNIC Blog*. https://blog.apnic.net/2024/04/19/a-multifaceted-look-at-starlink-performance-the-good-the-bad-and-the-ugly/

Baumann, W. (1990). Inertial navigation systems and their integration with GPS. *Navigation: Journal of the Institute of Navigation, 37*(3), 225–234. https://www.ion.org/publications/abstract.cfm?articleID=101796

Benedicto, J., Lugert, M., & Gerlach, C. (2013). Galileo: The European programme for global navigation services. *GPS World, 24*(6), 18–25. https://www.gpsworld.com/galileo-the-european-programme-for-global-navigation-services/

Easton, R. L. (1974). *Navigation system using satellites and passive ranging techniques. U.S. Patent No. 3,789,409*. United States Patent and Trademark Office. https://patents.google.com/patent/US3789409A/en

Enderle, W., Dilssner, F., Springer, T., Otten, M., Bruni, S., van Kints, M., & Montenbruck, O. (2024). GENESIS: A multi-technique geodetic observatory in space. *GPS Solutions*. https://doi.org/10.1007/s10291-024-01500-6

Enge, P., & Misra, P. (1994). Special issue on GPS: Signals, measurements, and performance. *Proceedings of the IEEE, 87*(1), 3–15. https://doi.org/10.1109/5.286849

Getting, I. A. (1964). The global positioning system. *IEEE Spectrum, 1*(10), 6–8. https://ieeexplore.ieee.org/document/11621506

Hein, G. W. (2020). Status, perspectives and trends of satellite navigation. *Satellite Navigation, 1*, 22. https://doi.org/10.1186/s43020-020-00022-0

Jin, S., Meng, X., Dardanelli, G., & Zhu, Y. (2024). Multi global navigation satellite system for earth observation: Recent developments and new progress. *Remote Sensing, 16*(24), 4800. https://doi.org/10.3390/rs16244800

Novák, A., Kováčiková, K., Kandera, B., & Sedláčková, A. N. (2024). Global navigation satellite systems signal vulnerabilities in unmanned aerial vehicle operations: Impact of affordable software-defined radio. *Drones, 8*(3), 109. https://doi.org/10.3390/drones8030109

Parkinson, B. W., & Spilker, J. J. (1996). *Global positioning system: Theory and applications* (Vol. 163). American Institute of Aeronautics https://doi.org/10.2514/4.866388

Register. (2024, March 4). Starlink offers ‘unusually hostile environment’ to TCP. *The Register*. https://www.theregister.com/2024/03/04/starlink_tcp_performance/

Sermanoukian Molina, I., van den IJssel, J. A. A., Gini, F., & Schoenemann, E. (2024). Analysis and enhancements of ESA/ESOC multi-GNSS solutions. In *9th International Colloquium on Scientific and Fundamental Aspects of GNSS*, Wrocław, Poland. https://www.cosmos.esa.int/web/gnss-colloquium