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The Reliability Factors of Application of Quadcopters in Logistics

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Abstract: The article is devoted to the assessment of the development and changes in logistics systems in the context of the introduction of unmanned drones for cargo delivery. Particular attention is paid to studies conducted by large international companies such as Amazon, UPS and DHL. The domestic analogue, Russian Post, is also actively involved in this area. The state of the legislative framework is analyzed, including infrastructure requirements and safety during the operation of drones. Recommendations for an integrated approach and cooperation with regulatory authorities are developed. The article focuses on the reliability factors of drone use, including battery charge, weight resistance, protection against theft and damage to cargo. In addition, the efficiency of delivery is calculated from an economic point of view. In addition, neural network models are studied and selected to optimize logistics.

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1 INTRODUCTION

The intensification of automation in the manufacturing and service sectors, driven by the growth of global demand for logistics services, requires innovative solutions to reduce the burden on labor resources. According to research presented in the Global Experience Review, the volume of commercial delivery using unmanned aerial vehicles (UAVs) has increased by 45% by 2024, which confirms their role as a key tool for optimizing supply chains. In the context of increasing market competition and environmental requirements in the form of a 30% reduction in carbon footprint, air cargo delivery using quadcopters stands out as a promising direction that minimizes the human factor and increases efficiency. The aim of the work is a comprehensive analysis of the integration of quadcopters into logistics systems, including an assessment of foreign and domestic experience (using the example of the Amazon Prime Air, DHL Parcelcopter projects and the unsuccessful initiatives of Russian Post), legislative restrictions and reliability factors such as energy efficiency and resistance to external influences (Mashnenkov, 2023). The subject of the research is the integration of quadcopters into logistics systems as an innovative solution for increasing the efficiency of cargo delivery (Kostin, 2021). The scientific novelty of the work lies in the systematization of multidisciplinary aspects of quadcopter integration from modeling neural network algorithms to the analysis of law enforcement practice. The results of the study can be used to develop regulatory measures and optimize logistics processes in the context of digital transformation (Matyukha, 2021).

2 MATERIALS AND METHODS

Methodologically, the work is based on a comprehensive analysis of publications over the past 6 years, with an emphasis on key technological, economic and legislative aspects of the use of unmanned aerial vehicles (UAVs) in logistics systems.

Let’s consider the parameters of flights.

1) Battery life: Lithium polymer batteries provide 20-30 minutes of flight time. More powerful sources such as solid-state batteries or hydrogen fuel cells are needed.

2) Weight capacity: Load capacity depends on the drone's design and materials. Increasing the load weight reduces maneuverability and stability.

3) Anti-theft: Alarm systems and GPS tracking prevent theft. Biometric identification helps prevent unauthorized access.

4) Damage protection: Reliable fastenings and shock-absorbing materials prevent damage to cargo during flight.

5) Sensors:

Ultrasonic: low cost, short range and accuracy.

Laser (LIDAR): high accuracy and range, but expensive and weather dependent.

Stereo vision: object recognition, requires complex processing.

RADAR: high resolution, but expensive and does not classify objects.

IMU (Inertial Measurement Units (MU): provide acceleration and angular velocity data but are prone to errors (Patrik, 2019)

To assess the efficiency of using drones, you can calculate the number of flights that one UAV can perform per shift under given parameters.

3 REVIEW

Quadcopters provide stable horizontal orientation and basic maneuvers (hovering, three-axis movement) due to dynamic adjustment of the thrust of four motors. The advantage of multicopter systems is their technological simplicity and low cost, which determines their dominance in the market. Delivery systems are implemented in two modes: fully autonomous (based on software with automation algorithms) and remotely controlled (Grankin, 2019). Control is carried out through a remote control with integrated mobile interfaces for transmitting telemetry and video data from onboard cameras (Barkova, 2022).

Operating modes:

1) Manual - continuous operator control.

2) GPS navigation – autonomous movement along specified routes with trajectory correction in real time.

Delivery algorithm:

1) Securing the load, activating the system.

2) Route generation (30–40 sec) taking into account terrain, obstacles (power lines, buildings), airspace restrictions, population density and meteorological parameters.

3) Take-off, transportation, cargo release, return along the original trajectory.

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Key performance factors: navigation accuracy, software adaptability, and minimization of human intervention. (Pustokhina, 2021)

Amazon Prime Air - Small cargo delivery, using balloons as logistics centers. Achieved reduced delivery time, but limited cargo weight.

DHL - Delivery to hard-to-reach regions, transportation of medicines. Successfully tested in various conditions, but requires reliable navigation.

UPS - Using a postal van as an airfield for drones. Achieved increased service speed, reduced driver labor costs.

Russian Post - Unsuccessful attempt to demonstrate delivery, drone collided with a building. The need to increase the stability and autonomy of technologies, as well as taking into account external factors (Wi-Fi interference) was reached (Mashnenkov, 2023)

4 PROBLEMS

An analysis of the regulatory challenges to the introduction of unmanned aerial vehicles (UAVs) into the delivery of goods shows significant obstacles. Delivery involves placing orders online and transporting goods using UAVs. To ensure safety, separation of airspace between manned aircraft and drones is required, with a maximum flight altitude of 400 feet (about 122 meters) for drones, fig.1.

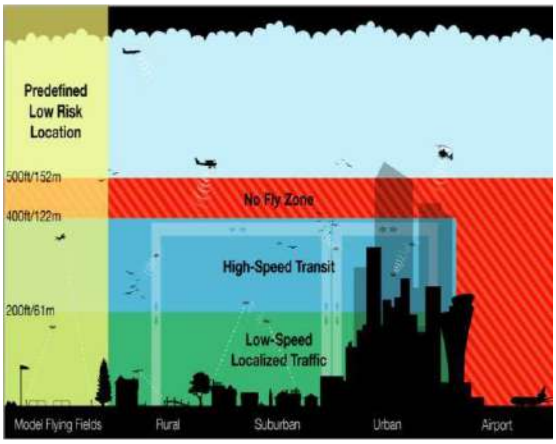

Figure 1: Separation of airspace between manned aircraft and drones.

The use of UAVs requires clear legal regulation, determined by the Decree of the Government of the Russian Federation and the Air Code. Key aspects of regulation:

1) Classification of UAVs (Articles 8, 33, 37 of the Air Code of the Russian Federation):

Up to 150 g: not subject to registration.

150 g – 30 kg: mandatory state registration (the bulk of household and commercial models).

Over 30 kg: state registration (used by special organizations).

For the last two categories, aviation operating regulations apply.

2) Legal restrictions:

Prohibition of flights over people (prevention of injuries).

Limiting the circle of operators (excluding minors and intoxicated persons).

Regulation of frequency ranges to minimize interference.

3) Institutional requirements:

Mandatory registration/accounting (except for devices up to 150 g).

Compliance with Federal Airspace Regulations (Resolution No. 138), including flight filings, routing, and altitude limits.

The problems include the lack of a unified definition of UAVs and operational risks such as security threats and disruption of public order. It is recommended to develop a separate regulation for UAVs, including criteria for operator certification and a list of prohibited areas, and to create a specialized infrastructure.

5 FACTORS RELIABILITY

Calculating the number of flights: Let's assume that the average speed of the drone is:

1) V = 36 km/h = 10 m/sec.
2) One way distance: S = 3 km = 3000 m.
3) Loading and unloading time: $t_{norp} = 10$ min.

Calculation of time for one flight:

$$t_f = \frac{S}{V} = \frac{3\ km}{36\ km/h} = 0{,}083\ h = 5\ min, \tag{1}$$

where t_f – time in transit without loading and unloading and then we have:

$$t_{one.f} = \frac{2S}{V} + t_{load} = \frac{2 \cdot 3000}{10} + 600\ sec = = 20\ min, \tag{2}$$

where is $t_{one.f}$ the time for one flight, taking into account all factors.

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In 6 hours (360 minutes) one drone can accomplish:

$$N_f = \frac{t}{\frac{20\ min}{one.f}} = \frac{360\ min}{\frac{20\ min}{one.f}} = 18\ flights \quad (3)$$

When calculating the coverage area, everything depends on the drone's flight time. If the flight time is 30 minutes, then the one-way flight range is:

$$d_{max} = \frac{V \cdot t_f}{2} = \frac{10\ m/sec \cdot 30\ min \cdot 60\ sec}{2} = 9\ km \quad (4)$$

A diagram comparing drones and traditional delivery is presented in the chart below, fig.2.

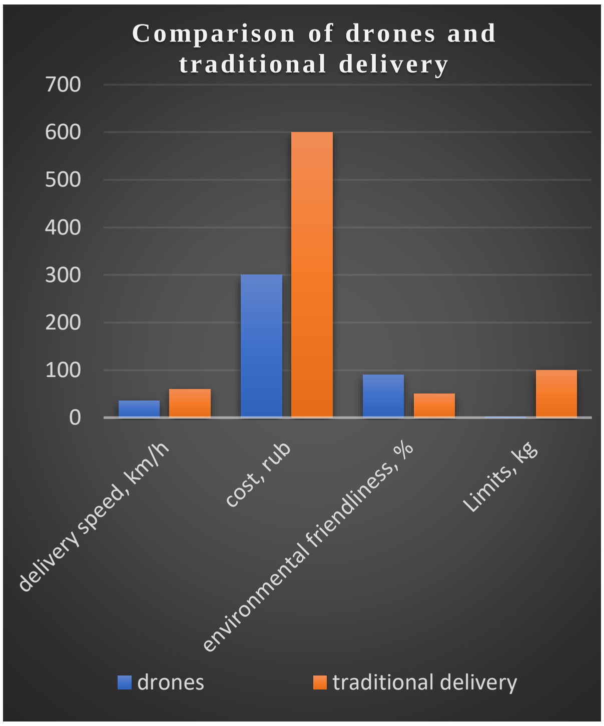

Figure 2: Comparison of drones and traditional delivery by aspects.

With an average cargo weight of 1.5 kg and a maximum drone load capacity of 3 kg, increasing the weight to 2.5 kg may result in fewer flights due to more frequent recharging or reduced flight speed. Let's designate the distance to the delivery point as L (in km) and calculate the travel time (there and back):

$$t = \frac{2L}{v} = \frac{L}{18}\ (hours) \quad (5)$$

Loading and charging time:

$$t_{load} = \frac{1}{6}\ (ч) = 10\ min \quad (6)$$

Therefore, the total time for one flight:

$$t_f = t + t_{load} = \frac{L}{18} + \frac{1}{6} = \frac{L}{18} + \frac{3}{18}\ (hours) \quad (7)$$

This means that when calculating the number of flights for a drone with 6 hours of operation (t_{oper} = 6 (h)):

$$N_f = \frac{t_{oper}}{t_f} = \frac{6}{\frac{L+3}{18}} = \frac{6 \cdot 18}{L+3} = \frac{108}{L+3} \quad (8)$$

With a cargo weight of 2.5 kg, the drone can only carry one load per flight. To plot the graph, the calculations show:

For L = 1 km - N = 27 flights;
For L = 2 km - N = 21 flights;
For L = 3 km - N = 18 flights;
For L = 4 km - N = 15 flights;
For L = 5 km - N = 13 flights.
Let's show that in fig.3.

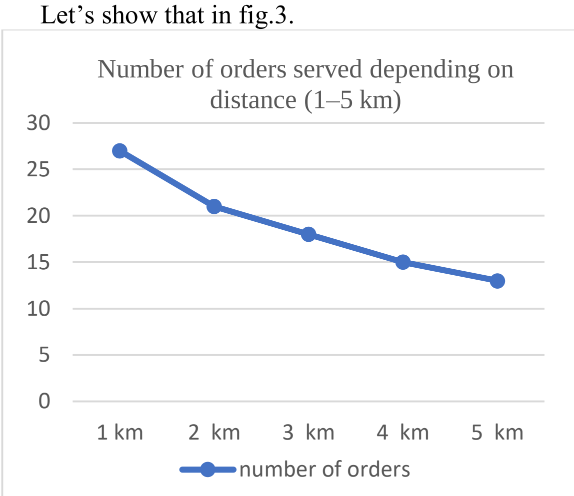

Figure 3: Number of orders served depending on distance (1–5 km).

4 NEURAL NETWORK MODELS

The integration of artificial intelligence (AI) and machine learning (ML) into quadcopter control solves key logistics problems: route optimization, energy consumption forecasting and equipment diagnostics.

At task minimizing delivery times and avoiding obstacles in real time.

Models:

1) "Gradient Descent" – Used to find the local minimum of the route cost function. The formula for updating parameters is:

$$\theta_{\text{new}} = \theta_{\text{old}} - \alpha \cdot \nabla J(\theta), \qquad (9)$$

where α is the learning step, ∇ J(θ) is the gradient of the loss function, which depends on distance, obstacles and weather conditions.

2) "Reinforcement learning (RL)" - this neural network learns to choose optimal routes through interaction with the environment. When the weather changes (for example, the wind increases), the RL model recalculates the route using LIDAR and GPS data. Delivery time is reduced by 15-20% compared to static algorithms.

When the task is to give an accurate calculation of the remaining battery charge taking into account the load and external factors.

Models:

3) " Linear Regression" - Used to calculate the exact relationship between energy and distance:

$$E = \theta_0 + \theta_1 \cdot L + \theta_2 \cdot m + \theta_3 \cdot v_{\text{ветра}}, \qquad (10)$$

where E is energy (W h), L is distance (km), m is load weight (kg), $v_{\text{ветра}}$is wind speed (m/s).

For a drone with a load of 2 kg and a distance of 5 km:

1. Energy forecast: $E = 1200 + 150 \cdot 5 + 200 \cdot 2 = 2350$Wh.
2. The energy forecast error is reduced to 5% versus 15% for classical methods (Savitsky, 2017).

5 RESULTS AND DISCUSSION

Therefore, it should be made the results.

1. Technological efficiency:

Quadcopters reduce delivery time by 50–70% for loads up to 3 kg, but are limited by autonomy (20–30 min) and load capacity (2–3 kg).

Calculations showed that with a range of 3 km, the drone makes 18 flights in 6 hours, but increasing the load weight to 2.5 kg reduces the number of flights by 25%.

2. Legislative barriers:

The lack of uniform international standards and duplication of terms in the Russian Air Code complicate the integration of UAVs.

The need to separate airspace (up to 122 m) and create restricted areas has been identified.

3. Reliability factors :

Limiting parameters: battery capacity (2350 Wh at 5 km), vulnerability to weather, risks of cyber attacks.

Optimal sensors: RADAR (high resolution) and stereo vision (obstacle recognition).

4. Neural network models :

The reinforcement learning algorithm reduces delivery times by 15-20% by adapting to wind and obstacles.

Linear regression reduces the error in energy consumption forecasting to 5%.

6 CONCLUSIONS

Therefore, it should be made the conclusion of the investigation.

1. Analysis results:

Quadcopters demonstrate high efficiency in delivering light loads (up to 3 kg), reducing delivery time by 50–70%. However, their use is limited by load capacity (2–3 kg), autonomy (20–30 min) and vulnerability to weather conditions.

Legislative barriers include the lack of uniform international standards, duplication of terms in the Russian Air Code, and the need to separate airspace between UAVs and manned aircraft.

Key reliability risks: limited battery capacity, threats of cyber attacks, dependence on multi-sensor systems: GPS, LIDAR, IMU (Gonta, 2023).

2. Practical recommendations:

Regulatory measures: development of a specialized regulatory act for UAVs with the definition of prohibited zones, operator certification and flight altitude standards (up to 122 m).

Technical solutions: implementation of hybrid energy sources (hydrogen fuel cells), lightweight composite materials and multisensory systems (RADAR + stereo vision).

Organizational measures: creation of infrastructure (airports, operator training centers) and integration of drones into multimodal logistics chains.

3. Prospects:

Cost-effectiveness: Reduce shipping costs by 15-25% as technologies scale (Belozerov, 2024).

Eco-friendly: 30% reduction in carbon footprint compared to traditional transport.

Neural network models (gradient descent, reinforcement learning) allow optimizing routes and predicting energy consumption with an error of up to 5%. (Mashnenkov, 2023).

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