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Environmental Benefits of Using Quadcopters in Logistics

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Abstract: The article describes the advantages and disadvantages of using quadcopters in the delivery industries. A list of leading drone manufacturing companies is provided. Key technological parameters are considered, such as increased delivery speed, in comparison with ground transportation of small-sized cargo. Attention is paid to economic aspects and an assessment of cost reduction from the use of unmanned aerial vehicles, which were provided by such companies as Kiva Systems and ARK Investment Management. The possibility of saving money due to the lack of an urgent need for personnel and infrastructure is also highlighted. Domestic experience in using drones in logistics is touched upon. An analysis of the problems that complicate the implementation of quadcopters and ways to solve them is provided. Particular attention is paid to the possibility of using neural networks to improve the efficiency of drones and optimize energy consumption. A study of the environmental friendliness of using unmanned aerial vehicles is taken into account. Studies comparing the carbon footprint of drones and traditional transport are presented. A study of the environmental friendliness of using unmanned aerial vehicles is taken into account. Research compares the carbon footprint of drones and traditional transport.

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1 INTRODUCTION

Cargo delivery is an integral part of production and trading activities. This area requires constant improvement due to the development of infrastructure and the growth in the number of consumers. Transportation of goods using traditional methods, such as trucks and cars, creates an additional burden on traffic and increases the final price of the product, taking into account the cost of gasoline and human labor. Modern technological advances inevitably change traditional approaches to logistics and transport, opening up new horizons in the field of delivery. One of the most promising and innovative trends is the use of quadcopters for cargo delivery. This innovation in logistics promises to improve the methods of cargo transportation, offering faster, more economical and reliable solutions (Mashnenkov, 2023). The specifics of drone transportation opens up promising ways of their application and contributes to significant savings on personnel for transport, manufacturing and trading companies delivering goods (Belozerov, 2023). The determining factor is that the technology for quadcopter delivery is already available, and the demand for this service is growing rapidly. Despite certain problems and limitations, such as the direct cost of quadcopters and their components, as well as repair costs, unmanned aerial vehicles may well become the main means of delivering goods in the next 10-15 years (Patrik, 2019). Technological features of logistics systems using unmanned aerial vehicles will allow the mass introduction of quadcopters into everyday life, increasing the cost-effectiveness of cargo delivery and reducing the negative environmental impact of transport on the environment.

2 MATERIALS AND METHODS

The methodological basis of the work is a comprehensive analysis of publications over the past 7 years, with an emphasis on key technological, economic and environmental aspects of the use of unmanned aerial vehicles (UAVs) in logistics systems. The analysis was carried out by comparing the costs of delivery using drones and traditional ground transport. A method for optimizing the energy consumption of quadcopters was also applied using neural network algorithms to predict energy costs and optimize flight routes. Theoretical calculations included an analysis of aerodynamic characteristics, thrust forces and air resistance, as well as the calculation of flight trajectories with minimal energy costs.

3 GENERAL REVIEW

Currently, there are more than 100 companies in the world that produce quadcopters for various purposes. However, the leading positions in the world market are held by enterprises from China, the USA and France, fig.1.

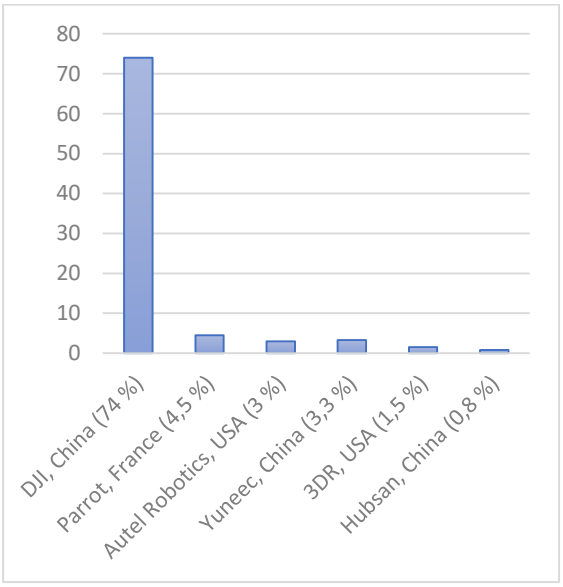

Figure 1: Popular Quadcopter Manufacturers.

Chinese companies dominate the industry thanks to their strong manufacturing infrastructure and significant foreign investment. The development of technology and microelectronics has allowed this country to become a leader in the civilian quadcopter segment, covering entry-level and professional models. The estimated profit of the leading drone manufacturers for 2023 was:

1. DJI - $ 4 billion.
2. Parrot - $ 107 million.
3. Autel Robotics - $ 31 million.
4. Yuneec - $ 60 million (Gonta, 2023).

4 ECO-FRIENDLY DRONES

Delivery of goods produces approximately 24% of global carbon dioxide emissions, which affect climate change. The largest share of CO2 comes

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from cars (48%) and trucks (16%). The latter are more often used in long-distance delivery, while the former can be used at the "last mile" stage, when the goods are delivered directly to the buyer. Quadcopters use electrical energy, and are thus more environmentally friendly compared to cars and trucks that run on fossil fuels.

The electricity required to operate drones is partially obtained by burning coal. This process is accompanied by gas emissions, but a comparison with the CO2 emissions of traditional delivery methods shows that UAVs pollute the atmosphere less. Also, some of the electrical energy comes from renewable sources (in particular, from solar or wind power plants), which significantly reduces the amount of carbon dioxide produced. This helps to reduce air pollution, especially in urban areas. In 2018, a group of scientists published a study in the journal Nature Communications in which they attempted to assess the environmental efficiency of drone delivery in the United States and compare it to traditional courier trucks.

Different parts of the country have renewable energy infrastructure, such as solar, which means that charging drones will result in different amounts of carbon dioxide emissions depending on the location. In the study, the scientists analyzed CO2 emissions in two extreme cases: the green state of California and the less "green" state of Missouri. A small drone operating in a warehouse in California would be responsible for emitting about 430 grams of CO2 per package, compared to 915 grams for a truck. But in less "green" Missouri, a small drone would be responsible for 850 grams of CO2 per package, while a truck would be responsible for 1,100 grams. So in California there would be a 53% savings on emissions, and in Missouri - 23%. Therefore, on average, quadcopters will be 38% more efficient.

According to a study by UVL Robotics, using drones to deliver packages in urban areas could reduce carbon dioxide emissions by 30-50% by 2030. This assumption is due to the fact that the absence of idle vehicles during loading and unloading should reduce associated carbon dioxide emissions.

One of the world's largest parcel delivery companies, UPS, uses ORION technology based on artificial intelligence. It is based on advanced algorithms and machine learning and is able to optimize delivery routes in real time. Since its launch, the tool has saved the company 160 million km and 45 million liters of fuel per year, which significantly reduces the negative carbon footprint.

5 ECONOMIC ASPECTS

One of the most significant advantages of drones is the cost of delivery. In the short term, quadcopters can reduce costs due to more direct and faster routes. The reduction in cost is influenced by the lack of need for personnel. Autonomous aircraft can operate without drivers, which reduces the cost of salaries and training of personnel (Kostin, 2021). Less infrastructure costs are required, since drones can take off from small sites and do not require the creation of a complex road network.

The disadvantage at the moment is the cost of quadcopters and their components. Maintenance and replacement can be expensive, but as technology advances, they will become cheaper. Even now, despite the high initial costs of purchasing drones and their operation, in the long run they can reduce overall delivery costs, especially as the scale of use increases and the cost of technology decreases.

It is worth considering the calculations of cost savings from the use of unmanned aerial vehicles. The co-founder of Kiva Systems, a company focused on the operation and research of drones, estimated the cost of delivering cargo weighing no more than two kilograms "on the last mile". It was 10 cents (as of 04/28/2019). When using ground transport to transport cargo of similar parameters, the price varied from 2 to 8 dollars. There are other estimates. The research company ARK Investment Management calculated the cost of transporting cargo in 30 minutes. It was equal to one dollar (Epifanov, 2016).

In Russian practice, an example of cost savings when delivering small-sized cargo by quadcopters is the Yota Company. In the fall of 2015, an experimental project was launched to transport SIM cards by drones in Moscow. Delivery of one SIM card by drone made it possible to reduce costs from 500 to 400 rubles (Tsarev, 2019).

An important detail is the speed of delivery. Modern quadcopters, independent of traffic density, can reach speeds of up to 60–100 km/h, allowing them to deliver small loads faster than cars that encounter traffic jams and road repairs, which can significantly slow down the transportation process (Kostin, 2021). Taking into account road delays, the average speed of ground delivery is 20–30 km/h. Time can be saved by not having to transport goods through several warehouses with subsequent unloading and loading of goods.

Drones can provide the greatest effect in reducing delivery times due to a departure from the traditional model of organizing logistics networks.

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In the Russian Federation, almost every parcel passes through an intermediate point - Moscow, regardless of the point of origin and destination (Grankin, 2019). This is due to the lack of direct flights between many cities in Russia. The creation of a decentralized transport network would provide the opportunity to dynamically redistribute goods. Let us provide a comparative analysis of cargo delivery using ground transport and an unmanned drone, taking into account speed, cost, readiness time, distance traveled on one charge or refueling, and the volume of carbon dioxide emissions (Abramova, 2020), fig.2.

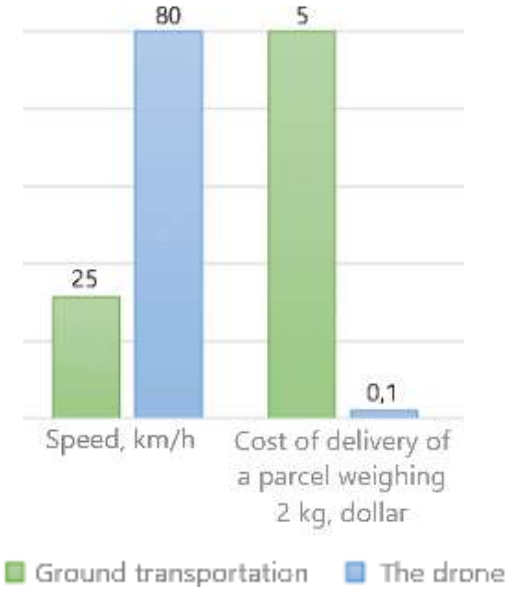

Figure 2: Comparison chart of cargo delivery using ground transport and drone.

Thus, based on data from Ernst & Young, it can be said that when delivering a small parcel over a relatively short distance, the advantage of a drone can be 37% in cost and 60% in time (Abramova, 2020).

6 OPTIMIZATION

The rapid development of neural networks, machine learning technologies and computer vision opens up new possibilities for the use of drones (Mokronos, 2023).

Optimization of energy consumption during quadcopter flights is an important task for increasing the efficiency of cargo delivery. The use of AI and neural networks provides new opportunities for predicting energy costs, optimizing flight routes and managing battery charge. In aerodynamics, neural networks are trained based on data obtained from experiments or numerical simulations. After training, it can predict aerodynamic characteristics based on input data.

Let us consider a method for optimizing a quadcopter flight, which is based on calculating the movement of the UAV as a result of giving various control commands.

To analyze systems that simultaneously move in space and rotate around their axis, a combination of two coordinate systems (CS) is used: one fixed (tied to the Earth) and the other moving. The fixed CS will be designated as OXYZ, and the moving one - O'X'Y'Z'. Thus, to transform coordinates from a fixed system to a moving one, the transformation matrix C is used:

$$C = \begin{pmatrix} cos\theta \cdot cos\psi & cos\theta \cdot sin\psi & -sin\theta \\ sin\psi \cdot sin\,\theta \cdot cos\,\psi - cos\,\varphi \cdot sin\,\psi & sin\,\varphi \cdot sin\,\theta \cdot sin\,\varphi + cos\,\varphi \cdot cos\,\psi & sin\varphi \cdot cos\theta \\ \cos\varphi \cdot \sin\theta \cdot \cos\psi + sin\varphi \cdot \sin\psi & sin\,\varphi \cdot sin\,\theta \cdot sin\,\psi - sin\,\varphi \cdot cos\,\psi & cos\,\varphi \cdot cos\,\theta \end{pmatrix} \quad (1)$$

To go from the moving coordinate system O'X'Y'Z' to the fixed one OXYZ, the transposed matrix CT is used. In this case, the angle φ is responsible for the rotation of the apparatus around the axis O'X', the angle θ is responsible for the rotation around O'Y', and the angle ψ is responsible for the rotation around O'Z'. For the equation of motion of the apparatus, it is necessary to take into account all the forces acting on it: gravity, propeller thrust and air resistance. In addition to these main forces, the apparatus is also affected by less significant forces. Below is a general form of the equation describing the influence of these forces on the apparatus:

$$\bar{F}_{final} = \bar{F}_{weight} + \bar{F}_{final} + \bar{F}_{thrust} + \bar{F}_{extra}\,, \quad (2)$$

where $\bar{F}_{final}$ – the resulting force; $\bar{F}_{weight}$ – the force of gravity; $\bar{F}_{thrust}$ – the thrust force of the propellers; $\bar{F}_{extra}$ – various additional forces whose influence is negligible in this case.

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The expression for the force of gravity has the following form:

$$\begin{cases} F_{weight} = \begin{pmatrix} 0 \\ 0 \\ F_{weight} \end{pmatrix}, \\ F_{weight} = m \cdot g \end{cases} \quad (3)$$

where F_{weight} – component of gravity along the O'Z' axis; m — the mass of the apparatus; g — the acceleration of gravity.

The expression for the thrust force of the propellers is as follows:

$$\begin{cases} F_{thrust} = \begin{pmatrix} F_{thrustX} \\ F_{thrustY} \\ F_{thrustZ} \end{pmatrix} = C^T \cdot \begin{pmatrix} 0 \\ 0 \\ F_{thrustZ'} \end{pmatrix}, \\ F_{thrustZ'} = K_1 \cdot R_1^2 \cdot f_1^2 + K_2 \cdot R_2^2 \cdot f_2^2 \\ +K_3 \cdot R_3^2 \cdot f_3^2 + K_4 \cdot R_4^2 \cdot f_4^2 \end{cases} \quad (4)$$

where K — the propeller thrust coefficient, R — the propeller radius, a f — ts rotation frequency. It is assumed that all four propellers are identical in their physical characteristics, and only the rotation frequency differs. The exception is when it is necessary to change the direction of motion, such as hovering or vertical movements (ascent and descent), when the rotation frequency of all four propellers becomes the same.

The thrust of each propeller depends on its physical characteristics, as well as on the parameters of the corresponding engine. Therefore, for simplicity, we can abandon the cumbersome full expression for the thrust of all propellers and use a more compact form:

$$F_{thrustZ'} = F_{thrust1} + F_{thrust2} + F_{thrust3} + F_{thrust4} = \sum_{i=1}^{4} F_{thrust}, \quad (5)$$

where $F_{thrust1..4}$ – the thrust force of each of the propellers, determined by the parameters of the propeller and the motor.

To determine the aerodynamic drag, you must first enter the speed at which the apparatus moves relative to the surrounding air (or vice versa, the speed of the air flow relative to the apparatus). This value is affected by both the movement of the apparatus itself and the movement of air masses (for example, wind). If we designate the speed of the apparatus (the center of mass of the apparatus) relative to the air as V', then it can be expressed as follows:

$$\begin{pmatrix} V'_{X'} \\ V'_{Y'} \\ V'_{Z'} \end{pmatrix} = C \cdot \begin{pmatrix} V'_{X'} \\ V'_{Y'} \\ V'_{Z'} \end{pmatrix} = C \cdot \begin{pmatrix} V_X - U_X \\ V_Y - U_Y \\ V_Z - U_Z \end{pmatrix}, \quad (6)$$

where V' – velocity of the center of mass of the apparatus relative to the air environment, V – the speed of the device relative to a fixed coordinate system (Earth), and U – air flow (wind) speed in the same coordinate system (relative to the Earth).

Using these relationships, we can derive an expression for the air resistance force:

$$F_{res} = \begin{pmatrix} F_{resX} \\ F_{resY} \\ F_{resZ} \end{pmatrix} = \begin{pmatrix} D_{hor} \cdot V'_X \cdot |V'_X| \\ D_{hor} \cdot V'_Y \cdot |V'_Y| \\ D_{vert} \cdot V'_Z \cdot |V'_Z| \end{pmatrix}, \quad (7)$$

where D_{hor} – coefficient of air resistance in the horizontal plane, and D_{vert} – coefficient of air resistance in the vertical plane. These coefficients are determined experimentally.

It is important to note that to take into account the direction of the air resistance force, instead of the square of the speed, it is necessary to use the product of the speed with the appropriate sign, multiplied by the absolute value of the speed. Otherwise, information about the direction of force application will be lost.

Having expressions for gravity, propeller thrust and air resistance, we can formulate a general equation of motion of the apparatus:

$$m \cdot \begin{pmatrix} a_X \\ a_Y \\ a_Z \end{pmatrix} = C \cdot \begin{pmatrix} 0 \\ 0 \\ F_{thrustZ'} \end{pmatrix} - \begin{pmatrix} 0 \\ 0 \\ F_{weightZ'} \end{pmatrix} - \begin{pmatrix} F_{resX} \\ F_{resY} \\ F_{resZ} \end{pmatrix}, \quad (8)$$

where m – weight of the device; a – acceleration (first derivative of velocity) of the device.

Based on these relationships (1)-(9), the use of a neural network to reduce energy costs in the system described in the algorithm can be an effective tool that allows analyzing complex dependencies and dynamic changes in the apparatus control system.

The neural network can be trained on historical data on the apparatus's motion, its orientation and external conditions (wind, temperature, speed and other factors) to predict the optimal tilt angles (φ, θ, ψ) and propeller rotation frequency (f1, f2, f3, f4) for each specific state of the apparatus.

Let's rewrite the expression in full form:

$$m \cdot \begin{pmatrix} a_X \\ a_Y \\ a_Z \end{pmatrix} = \left(C^T \cdot \begin{pmatrix} 0 \\ 0 \\ \sum_{i=1}^{4} F_{thrust} \end{pmatrix} - \begin{pmatrix} 0 \\ 0 \\ m \cdot g \end{pmatrix} - \begin{pmatrix} D_{hor} \cdot V'_X \cdot |V'_X| \\ D_{hor} \cdot V'_Y \cdot |V'_Y| \\ D_{vert} \cdot V'_Z \cdot |V'_Z| \end{pmatrix} \right) \quad (9)$$

Artificial intelligence receives input data: apparatus speed (V), tilt angles, external factors (such as wind), drag coefficients, based on which it predicts how the tilt angle or propeller rotation frequency parameters should be changed to minimize energy costs. The system automatically adjusts these parameters in real time. This allows to reduce thrust, thereby reducing energy costs (Kotsko, 2023; Makhonin, 2021).

The neural network can be trained on large volumes of air resistance data (including taking into account the influence of weather conditions) to calculate air resistance coefficients (Dhor and Dvert). It predicts when and how to change the trajectory, speed or angle of inclination to minimize aerodynamic drag. And then a model is used that predicts the minimum drag values for each specific operating mode of the device.

Planning the path and maneuvers of the device includes choosing the optimal trajectory with minimal energy costs depending on the current conditions. Trajectory optimization algorithms based on neural networks can predict the best routes with minimal energy costs, taking into account all external and internal factors. It is also possible to learn from data on various routes and maneuvers to use the least energy-consuming routes in the future (Savitsky, 2017).

The operation of motors and propellers can be optimized based on the analysis of their current parameters. The neural network analyzes current data on the state of the motors and propellers, as well as the speed and orientation of the device, after which the system adjusts the parameters of the motor and propellers to maintain optimal thrust with minimal energy consumption. In the process, the AI learns to optimize control in order to prevent excessive energy consumption, especially when changing the flight mode (for example, during vertical ascent or continuous movement). This will reduce engine overloads, which will increase their service life and long-term efficiency (Kotsko, 2023). Thus, this algorithm allows you to predict with high accuracy the movement of the device as a result of executing control commands, which makes it possible to calculate the energy consumption of the planned route. Having calculated several trajectories, the neural network can choose the least energy-consuming one, thereby ensuring the desired optimization of energy consumption.

7 RESULTS AND DISCUSSION

The main results of investigation should described the following sentences.

1. Advantages of Quadcopters:

Drones reduce delivery costs by eliminating the need for personnel and infrastructure. They are especially effective in last-mile deliveries.

2. Environmental Benefits:

Quadcopters reduce CO_2 emissions compared to cars and trucks. In regions with developed renewable energy infrastructure, emissions reductions can reach 53%.

3. Cost-Efficiency:

Despite high initial costs, drones can reduce overall delivery costs. Savings are 37% in cost and 60% in time over short distances.

4. Energy Efficiency and Optimization:

Using artificial intelligence to optimize routes and manage energy consumption increases productivity. Neural networks help minimize energy consumption and improve drone performance.

5. Limitations:

High initial costs for purchasing and maintaining drones. Infrastructure in some regions limits their effectiveness. This is most noticeable in densely populated cities.

6. Development Prospects:

With the development of technology and renewable energy sources, quadcopters are expected to become a more profitable and faster way to deliver goods within the next 10-15 years.

8 CONCLUSIONS

The technology of cargo delivery using quadcopters is already quite developed and continues to improve. The development of automation systems and artificial intelligence opens up new opportunities for integrating drones into existing logistics processes.

This allows for the creation of more efficient and reliable solutions for the delivery of goods in today's market.

Quadcopters that use electric energy are significantly less harmful to the environment compared to traditional modes of transport that run on fossil fuels. Their use helps reduce carbon dioxide emissions, which is especially important for urban areas. Given the growth of renewable energy production, the environmental efficiency of quadcopters will only increase in the future.

Drones show high economic efficiency. Despite the high initial costs of purchasing and operating quadcopters, their use can significantly reduce personnel and infrastructure costs, as well as reduce delivery costs due to more direct and faster routes. This makes quadcopters particularly advantageous for delivering small-sized goods in dense traffic conditions and complex road networks, including at the final stage of transportation. The development of algorithms to minimize energy consumption improves the operating time of drones and reduces their operating costs (Mashenkov, 2023).

The use of artificial intelligence and neural networks to optimize flight routes and manage the energy costs of quadcopters opens up new horizons for increasing their efficiency. The development of algorithms to minimize energy consumption improves the operating time of drones and reduces their operating costs, making them even more competitive compared to traditional transport. Also, the use of AI technologies increases the autonomy of systems, which is important in situations where the speed of decision-making and execution of actions is a critical factor (Andrievsky, 2023).

To summarize, it can be expected that with the development of technology and the growing demand for unmanned systems, quadcopters will become the main means of delivering goods in the next 10-15 years (Gonta, 2023).

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