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ENERGY AND OPERATIONAL ANALYSIS OF CONTINUOUS SURVEILLANCE SYSTEMS BASED ON MULTIROTOR UAVS

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***ABSTRACT** Drones are used in many applications, including continuous surveillance and monitoring. They can be used in cases, when the deployment time of surveillance system should be as fast as possible, or when a centralized electric grid is not available: accompanying fire extinguishing and liquidation of emergencies, 24/7 surveillance of the border area, monitoring of open-air events. They also can be used as stationary cameras, carrier of means of radio-electronic intelligence, weather conditions intelligence in airport areas, monitoring of crops, etc. The optimal solution for surveillance of large areas, such as critical infrastructure facilities (nuclear power plants, dams), and military facilities (field bases, ammunition warehouses), is the utilization of a group of drones when a single drone will observe his sector. The development of such systems and analysis of conditions for continuous surveillance taking into account the limitations of drone batteries require deep studies of drone energy consumption in various operation modes. The paper proposes a comprehensive investigation of operation modes of continuous surveillance systems, based on drones with electric-supplied propulsion systems, and optimization of its parameters. In the study, a comprehensive analysis of drones' energy demands was done and conditions for continuous surveillance were found. Based on the parameters of DJI Mavic 2 Enterprise drone and with the use of regression analysis, the optimal flight profile was introduced, for which the maximal achievable distance to the observing point was calculated for the "ideal" case. The case of increasing the drone number for extension of achievable distance to the observation point was investigated and the optimal number of drones for each distance was found. A set of experiments with drone flights was conducted to update and improve the prediction of the drone's energy consumption during the flight. Finally, the conclusion was set that external parameters, such as wind speed and direction, can significantly decrease the achievable distance to the observing point.*
***Keywords:** continuous surveillance system; drone; energy consumption; flight profile; charging station.*

ЕНЕРГЕТИЧНИЙ ТА ОПЕРАЦІЙНИЙ АНАЛІЗ СИСТЕМ БЕЗПЕРЕРВНОГО СПОСТЕРЕЖЕННЯ НА ОСНОВІ БАГАТОРОТОРНИХ БПЛА

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***АНОТАЦІЯ** Дрони застосовуються у багатьох сферах, зокрема для систем безперервного спостереження та моніторингу. Вони можуть бути використані у випадках, коли час розгортання такої системи спостереження має бути максимально швидким та зазвичай коли централізована електрична мережа недоступна: гасіння пожеж та ліквідація надзвичайних ситуацій, цілодобове спостереження за прикордонною зоною, моніторинг заходів під відкритим небом. Вони також можуть бути використані як стаціонарні відеокамери, носій засобів радіоелектронної розвідки, розвідки погодних умов у районах аеропортів, моніторингу посівів, тощо. Оптимальне рішення для спостереження за великими територіями, такими як об'єкти критичної інфраструктури (АЕС, греблі), так і військових об'єктів (польові бази, склади боєприпасів), є застосування груп дронів, коли один дрон буде спостерігати за своїм сектором. Розробка таких систем та аналіз умов безперервного спостереження з урахуванням обмежень батарей дронів потребує глибоких досліджень енергоспоживання дронів у різних режимах роботи. У статті запропоновано комплексне дослідження режимів роботи системи безперервного спостереження на основі дронів з електроприводом та оптимізація її параметрів. У ході дослідження було проведено комплексний аналіз енергетичних потреб дронів і знайдено умови для постійного спостереження. На основі параметрів дрона DJI Mavic 2 Enterprise та з використанням регресійного аналізу введено оптимальний профіль польоту, для якого розраховано максимально досяжну відстань до точки спостереження для «ідеального» випадку. Було досліджено випадок збільшення кількості дронів для збільшення досяжної відстані до точки спостереження та знайдено оптимальну кількість дронів для кожної відстані. Було проведено серію експериментів з польотами дронів, щоб оновити та покращити прогноз споживання енергії дроном під час польоту. Нарешті було зроблено висновок, що зовнішні параметри, такі як швидкість і напрямок вітру, можуть значно зменшити досяжну відстань до точки спостереження.*
***Ключові слова:** система безперервного спостереження; дрон; енергоспоживання; профіль польоту; зарядна станція.*

Introduction

Continuous surveillance systems, equipped with cameras, are widely used for indoor and outdoor monitoring and protection of restricted areas – nuclear power plants, military bases, airports, etc. Outdoor stationary surveillance systems usually utilize tall existing buildings or specially made and located masts, where cameras are mounted. The design of such a surveillance system requires many cameras to cover all blind zones, many additional connections to the electrical grid for camera power supplies, and usually a lot of time for system deployment. With the wide spread of drones, equipped with high-precision cameras, the utilization of

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drones for 24/7 surveillance of a specific area has attracted considerable attention in recent years due to their real-time surveillance and hovering capabilities. Drone is a colloquial term for an unmanned aerial vehicle (UAV), commonly referred to as a quadcopter [1]. They can be used in cases, when the deployment time of surveillance system should be as fast as possible, or when a centralized electric grid is not available: accompanying fire extinguishing and liquidation of emergencies [2], 24/7 surveillance of the border area [3], monitoring of open-air events [4,5]. They also can be used as stationary cameras, carrier of means of radio-electronic intelligence [6], weather conditions intelligence in airport areas [7], monitoring of crops [8], etc. The optimal solution for surveillance of large areas, such as critical infrastructure facilities (nuclear power plants, dams), and military facilities (field bases, ammunition warehouses), is the utilization of a group of drones when a single drone will observe its sector [9] (Fig. 1).

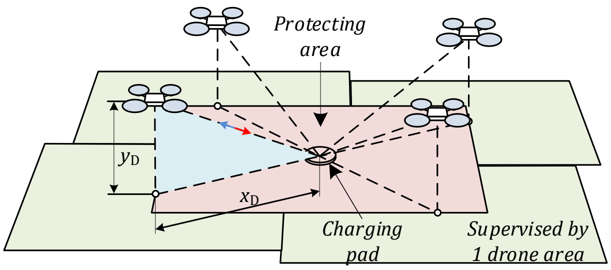

Fig. 1 – Drone system for perimeter surveillance (generalized concept)

The creation of such a drone group, or swarm, is a challenge of control, organization of flight profiles, energy supply, and recharging, and researchers all over the world are working on solving it. All those challenges are caused by limited flight time (up to 1 hour) for drones with the electric-powered propulsion systems. One of the possible solutions for recharging drones is wireless charging of batteries via existing electric power lines. Such technology was already theoretically approved and verified in the laboratory [10]. In addition, a continuous surveillance system along the borderline between the USA and Mexico utilizing the existing power line is studied in the article [11]. The main focus of the study was paid to the finding of the optimal drone’s speed to optimize the battery discharge and minimization of the charging time for wireless charging. Many researches are focused on the optimization of flight profile for energy efficiency. In the study [12], the issue of limited drone battery capacity in continuous surveillance systems is considered. The problem is proposed to be solved by the developed genetic algorithm that optimizing the drone’s route and position of charging pads for the battery charge. Some papers are focused on the optimization of the return route of the drone to the charging pad that take into account the changes of environmental conditions [13], but there are still some unresolved issues, such as an impact of wind gusts on the drone battery discharge.

Another possible solution for mentioned above issues is an automatized replacement of empty drone’s battery to preliminary charged. Studies [14–16] proposed a solution for an automatic battery replacement mechanism that allows to organize continuous surveillance by group of drones without manual battery replacement, along with scalable and reliable system usage. Catching the drone, replacing, recharging, and cleaning the battery are proposed there by means of a robotic system. Power supply of such a complex surveillance system can be assured by direct connection to the electric power line, or, for cases when centralized grid is not available, by means of energy storage and autonomous/renewable energy sources. Existing studies [17] have already investigated the improvement of surveillance system performance by means of the proposed control algorithm. The algorithm took into account the impact of the electricity produced by photovoltaic panels during the day in Egypt and managed the time planning of the continuous surveillance performed by drones.

As can be seen from the above analysis of the numerous studies, researchers already proposed various solutions for the improvement of energy performance of drone-based surveillance systems. This includes the implementation of battery replacement, wireless power transfer, energy storage, and photovoltaics technologies, as well as comprehensive control algorithms. At the same time, many issues of flight profile and high-level control systems for continuous uninterruptible surveillance systems are still not resolved. The effects of environmental conditions, such as wind gusts on the drone battery discharge and surveillance flight, optimal flight profile, and maximal distance from the charging pad to the observation point are some of them.

The paper proposes a comprehensive investigation of operation modes of continuous surveillance systems, based on drones with electric-supplied propulsion systems, and optimization of its parameters. In Chapter 2, the structure and general operating principles of the proposed surveillance system are described. Possible flight profiles of drones from the charging pad to the surveillance point and energy consumption patterns during the flight are discussed in Chapter 3. In Chapter 4 utilizing computer calculations, an optimal flight profile for DJI Mavic 2 drone and charge consumptions were found. The maximal achievable distance to the observation point, the influence of flight profile and number of drones on achievable distance to the observation are found in Chapter 5. Finally, in Chapter 6 results of experimental tests and updated by experimental data, results of simulations are presented.

In this article, “flight profile” refers to the comprehensive sequence of phases and performance metrics of an aircraft from takeoff to landing, "trajectory" denotes the precise path an object follows through space as influenced by forces acting upon it, and "flight route" specifies the predetermined navigation path an aircraft is planned to follow between departure and destination points.

The dimensions of the reconnaissance objects are not considered in the paper.

The objective of the work

The objective of the work is evaluating the optimal flight profile and number of drones that allow continuous surveillance at the maximum range based on the simulation and experimental verification.

Proposed surveillance system

The proposed continuous surveillance system, equipped with drones, is presented in Fig. 1. The main aim of such a system is continuous surveillance of the protective area perimeter by a set of drones, hovered in some defined points observation points. In general, the number of drones required to cover a perimeter depends on the drone's camera resolution and the length of the perimeter. The proposed system is centralized, which means there is only one charging pad in the centre of the protected area, where the connection with the power lines and charging of all drones are organized.

To ensure smooth continuous surveillance, the system consists of more drones than observation points: when some drones are hovering at observation points, some drones are charging at charging pads or flying to replace drones with low batteries. The minimum number of drones that support continuous surveillance in one observation point will be found later in the paper as the function of distance to this point.

The flight profile for each drone in the system in the first approximation is proposed in the study [18]. It includes vertical take-off until reaching the required altitude y_D, and then horizontal flight to the observation point, until reaching the coordinates (x_D; y_D). The energy consumption from take-off to observation point is stored and used to calculate the minimum required state-of-charge (SOC) level for returning home. After reaching observation point, the drone is hovering and transmitting the video stream to the central station. When the drone's SOC is close to minimum possible for returning home level, another drone is flying to replace it. After replacement drone is already in the observation point, "empty" drone returns to charging pad along the same flight route. So, the energy consumption for the part of flight from charging pad to observation point is crucial for the continuous surveillance, because it defines the time interval for replacement drone to start its flight. The simplified flight profile proposed in the study is shown in Fig. 1.

The flight route, trajectory or flight profile used in the study [18] requires a detailed study and enhancement to improve the energy characteristics based on the experimental data.

Possible flight profiles

To develop an optimal flight profile that fits most of the existing drones, it is necessary to analyse the main flight profiles that can be used in such systems. By modelling such profiles, it is possible to determine energy patterns or patterns that can affect the discharge of the drone and, as a result, increase the flight range. This approach will make it possible to find versatile characteristics of drones that will influence both the number of drones and the flight range.

The coordinate systems from the study [18] was chosen for the analysis, where the impact of the variation in the number of drones on the flight range was already investigated using computer simulation. Instead of 3D coordinate systems, an orthogonal 2D coordinate system, aligned for every observation point, is used for further calculations. The coordinate systems have the origin at the charging pad (0;0), and the destination point – observation point has coordinates (x_D;y_D). By using the data and calculations obtained in the study [18], it is possible to conclude the importance of flight time and current consumption in the number of drones and the maximum observation range calculation. To identify the most advantageous flight profile, from the energy consumption point of view, it is necessary to analyse three potential flight scenarios, shown in Fig. 2.

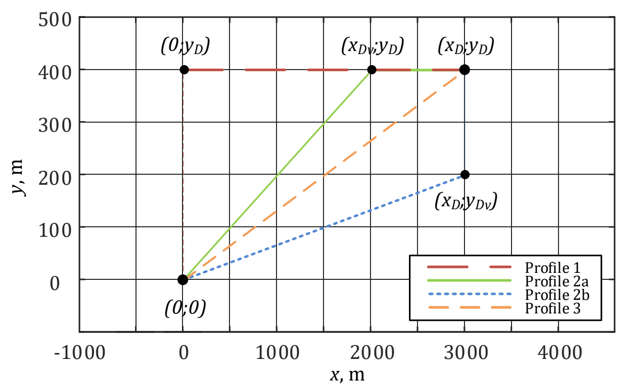

Fig. 2 – Possible flight profiles from charging pad to surveillance point

3.1 Flight profile 1

The first option of flight profile is shown in Fig. 2 as "profile 1", it is the same trajectory as it was proposed in the study [18]: horizontal take-off until the altitude of the observation point and then horizontal direct flight to the observation point. Such a flight profile provides the classic concept of flying to any point, which corresponds to the following parts: vertical take-off up to the required altitude, then horizontal flight to the observation point, hovering in the observation point until the charge drops to the minimum level, required for the returning. Horizontal flight in the reverse direction, and finally vertical landing for the battery recharging. The total charge Q_1 for the flight in the first flight profile can be calculated as the sum of the charge Q_{1top} (the flight to the observation point

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from landing zone), and Q_{1tol} (in the reverse direction – from the point of observation to the landing zone), according to equations 1 and 2:

$$Q_{1_{top}} = T_{1_{toff}} \cdot I_{toff} + T_{1_{hor}} \cdot I_{hor}, \quad (1)$$

$$Q_{1_{tol}} = T_{1_{tol}} \cdot I_{land} + T_{1_{hor}} \cdot I_{hor}, \quad (2)$$

where T_{1toff} – flight time from the point (0;0) to the point (0;y_D), hours; T_{1tol} – flight time from the point (0;y_D) to the point (0;0), hours; T_{1hor} – flight time from the point (0;y_D) to the point (x_D;y_D) and in the reverse direction, hours; I_{toff}, I_{hor}, I_{land} – total current consumption of drone's motors, flight controller, positioning and communication system during take-off, horizontal flight and landing, respectively, A.

Flight times, mentioned in equations (1) and (2) can be easily found through the coordinates (x_D;y_D) and flight speed in horizontal and vertical flight S_{hor} and S_{ver}, respectively. The second part in the equations – current consumption – in the first assumption can be taken as the constant value that depends only on the mentioned flight mode. In reality, the current consumption will also depend on the environmental conditions, such as wind speed and direction, and wind gusts. Such variations can be taken into account in the calculations only through statistical analysis based on numerous experimental tests.

In this article, although drones typically exhibit a lower descent speed compared to their take-off speed, the vertical speed for both ascent and descent is considered to be the same.

3.2 Flight profile 2

According to the second flight scenario ("profile 2a" and "profile 2b" in Fig. 2), the flight is carried out with a more complicated trajectory, consisting of the following two segments:

The first segment covers the flight from the point (0;0) to the point (x_{Dv};y_{Dv}) and back, is carried out straight in order to achieve the maximum horizontal and vertical speed S_{hor_lim}, S_{ver_lim}. The charge consumption $Q_{2\_top\_1}$ for the flight in the direction from the point (0;0) to the point (x_{Dv};y_{Dv}) and the charge consumption $Q_{2\_tol\_1}$ for the reverse direction can be calculated as follows:

$$Q_{2_{top_1}} = T_{2_{top}} \cdot I_{2_{top}}, \quad (3)$$

$$Q_{2_{tol_1}} = T_{2_{tol}} \cdot I_{2_{tol}}, \quad (4)$$

where T_{2_top}, T_{2_tol} – flight time from the point (0;0) to the point (x_{Dv};y_{Dv}) and back, I_{2_top}, I_{2_tol} – current consumption while gaining and lowering the flight altitude with S_{hor_lim} and S_{ver_lim} speed.

The second segment covers the flight from the point (x_{Dv};y_{Dv}) to the observing point (x_D;y_D) and in the opposite direction. On this segment, the flight is carried out either horizontally or vertically, depending on whether the drone will reach y_D (Fig. 2 – "profile 2a") or x_D ("profile 2b") faster. The time of reaching the corresponding points of the route can be determined by such inequalities:

if $T_{2_{hor}} - T_{2_{ver_t}} > 0$, than y_D is reached;
if $T_{2_{hor}} - T_{2_{ver_t}} < 0$, than x_D is reached;
if $T_{2_{hor}} - T_{2_{ver_t}} = 0$, than the coordinates of (x_{Dv};y_{Dv}) and (x_D;y_D) is equal.

In mentioned above equations T_{2_hor} and $T_{2\_ver\_t}$ are the flight time from the point (x_{Dv};y_{Dv}) to (x_D;y_D) depending on whether the drone will reach y_D or x_D faster.

Charge consumption on the corresponding segment is calculated according to the formulas:

$$Q_{2_{top_2}} = \left(T_{2_{hor}} - T_{2_{ver_t}}\right) \cdot I_{hor}, \ or$$
$$Q_{2_{top_2}} = \left(T_{2_{ver_t}} - T_{2_{hor}}\right) \cdot I_{toff}, \quad (5)$$

$$Q_{2_{tol_2}} = \left(T_{2_{hor}} - T_{2_{ver_l}}\right) \cdot I_{hor}, \ or$$
$$Q_{2_{tol_2}} = \left(T_{2_{ver_l}} - T_{2_{hor}}\right) \cdot I_{land}, \quad (6)$$

where $T2_{hor\_l}$,$T2_{ver\_l}$ – flight time from the point (x_D;y_D) to the point (x_{Dv};y_{Dv}) depending on whether the drone will reach y_{Dv} or x_{Dv} faster.

The total charge consumption for the flight Q2 can be defined as the sum of all the costs for the flight to the observation point (x_D;y_D) and in the opposite direction.

It should be noted, that for flights to distances exceeding 1 km, mostly the drone will first reach the required altitude, and only then will it move rectilinearly. Such a flight profile reflects the idea that the maximum speeds at the beginning of the flight will lead to a decrease in flight time compared to the first flight profile. In addition, the overall flight's charge consumption will decrease due to the lower current consumption in a horizontal flight.

The flight profile 2b (Fig. 2), in which the flight from the point (0;0) to the point (x_{Dv};y_{Dv}) is carried out "diagonally" is not considered due to the assumption that the energy consumption for the flight in such case will increase. This is due to the need to take into account the adjustment of the flight altitude after reaching the point y_{dv}=0 and further several changes of the flight path.

3.3 Flight profile 3

The flight profile 3 ("profile 3" in Fig. 2) assumes that the drone takes off from the point (0;0) and its speed and position are adjusted in such a way that the speed's vector will be directed to the point (x_{Dv};y_{Dv}). This flight profile is chosen based on the assumption that the energy consumption for the flight will be optimal due to the optimization of the movement speed, while the arrival time at the observation will be minimal.

The calculation of the total charge consumption for the flight Q_3 requires detailed calculations due to the change in the consumption current I_d. One of the available methods for determining I_d is the analysis of vertical and horizontal speed S_{ver}, S_{hor}, respectively, and searching of relationships between them and I_d. The charge consumption can be found as the sum of two parts Q_{3_top} (flight to the observation point) and (reverse direction) Q_{3_tol} according to the formulas:

$$Q_{3_{top}} = I_{d_{top}} \cdot T_{3_{top}}, \quad (7)$$

$$Q_{3_{tol}} = I_{d_{tol}} \cdot T_{3_{tol}}, \quad (8)$$

where I_{d_top} and I_{d_tol} - current consumption during the flight to and from observation point, respectively, A.

Accordingly, the flight time to the observation point T_{3_top} is calculated as the ratio of x_D to S_{hor} or y_D to S_{ver}, these values will be the same. To calculate S_{hor} and S_{ver}, data on the software limitation of drone's flight speed S_{v_lim} and S_{h_lim} can be used, Fig. 3 shows these limits and possible S_{hor} and S_{ver} as the function of x_D for y_D=400 m, S_{v_lim}=3 m/s and S_{h_lim}=15 m/s.

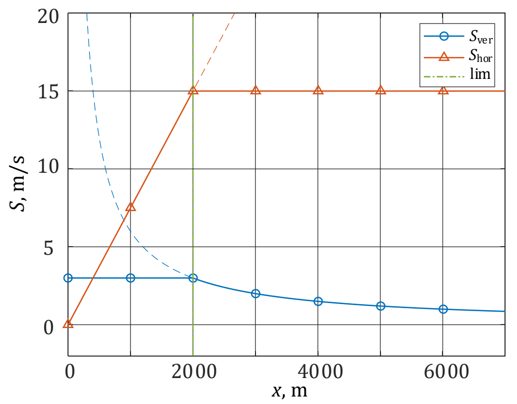

Fig. 3 – Dependency of S_{ver} and S_{hor} from x_D for y_D=400 m

So, finally S_{hor} and S_{ver} are calculated according to equations (9) and (10):

$$S_{hor} = \frac{S_{v_{lim}} \cdot x_D}{y_D}, \quad (9)$$

$$S_{ver} = \frac{S_{h_{lim}} \cdot y_D}{x_D}. \quad (10)$$

Simulation of flight profiles and selection the optimal

After the mathematical description of possible flight profiles, the following task is the choosing of the optimal one that has minimal charge consumption during the flight to the observation point and back. To calculate this charge, experimental data of current consumption for the drone DJI Mavic 2 Enterprise were used (Table 1).

As it can be seen, both S_{hor} and S_{ver} influenced on I_d. During the simulation, the speed limits were used the same as shown in Fig. 3 – S_{v_lim}=3 m/s and S_{h_lim}=15 m/s, y_D in the range of 100…500 m, and x_D in the range of 1000…7000 meters. To select the optimal flight profile, a maximum allowable charge consumption, Q_{lim} Q_{lim}, is set at 0.26 of SOC.

Table 1 – Current consumption I at various S_{ver} and S_{hor}

Parameter		S_{ver}, m/s	S_{hor}, m/s	I, A
from (0;0) to (x_D;y_D)	$I_{d\ top}$	3	15	12,5
	I_{hor}	0	15	11
	I_{toff}= I_{loit}	3	0	5,5
from (x_D;y_D) to (0;0)	$I_{d\ tol}$	3	15	8,5
	I_{hor}	0	15	11
	I_{land}	3	0	4,5

Charge consumption for flight profile 1

According to the first flight profile, charge consumption Q1 consists of two parts Q_{1_top} and Q_{1_tol} that are calculated by equations (1) and (2). Results of the calculations in MATLAB software are shown in colour map representation in Fig. 4a, which allows plotting on the graph in two-dimensional space using a colour scale that displays the intensity of Q values in relation to x_D and y_D. The points in the center of the plot cells indicate that the flight charge consumption for the pair, x_D and y_D is lower than Q_{lim}=0.26 of SOC. The simulation results show that the maximum value of Q is reached at x_D=4000 meters and y_D=200 meters. At the same time, the graph shows that the maximum range can be reached at lower altitudes. This is explained by the significant costs for take-off to a certain altitude with an unchanged value of the flight range, which affects the result. This shows the correctness of the selected direction of the study by comparing flight profiles 2 and 3.

Charge consumption for flight profile 2

Results of the calculation of charge consumptions Q_{2_top} and Q_{2_tol} for the flight profile 2 are shown in Fig. 4b. As can be seen, for x_D>2000 m, the value of y_D does not affect the total charge consumption for the flight, which is explained by the fact that the vertical flight is neglected. After reaching the altitude y_D, the following part of the flight is carried out horizontally with lower current consumption that is the benefit of the second flight profile compared to the first one.

Charge consumption for flight profile 3

To calculate Q_3, the linear regression method [19] that utilized the model with the relationship between the dependent variable and the matrix of independent variables was used to predict I_d values based on two input factors: S_{ver} and S_{hor}. The representation of the model includes the model formula, estimated coefficients, and accumulated statistics [20]. The model in general can be expressed by the following equation:

$$y_i = \beta_0 + \beta_1 x_{i1} + \dots + \beta_p x_{ip} + \varepsilon_i, i = 1, \dots, m, \quad (11)$$

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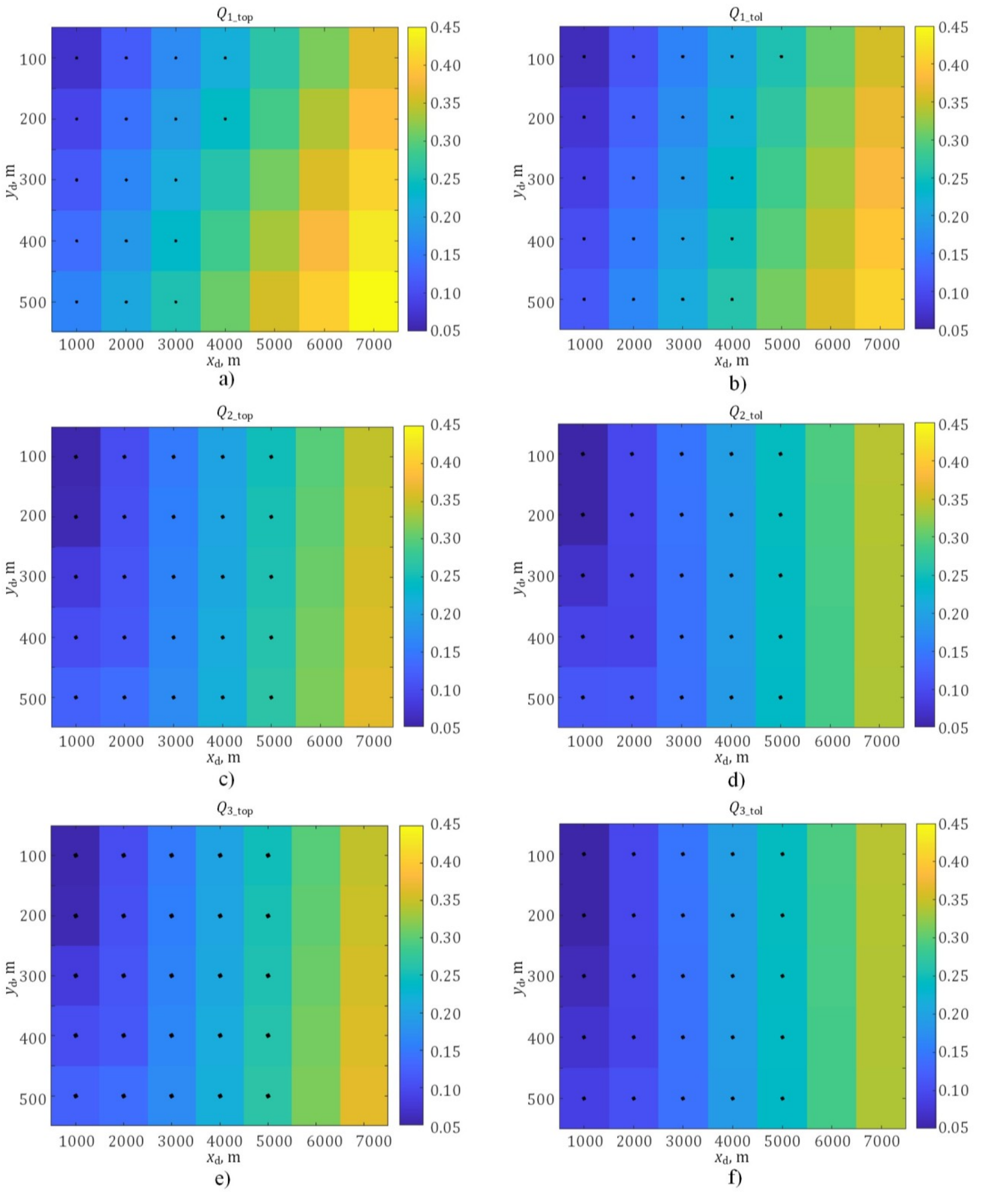


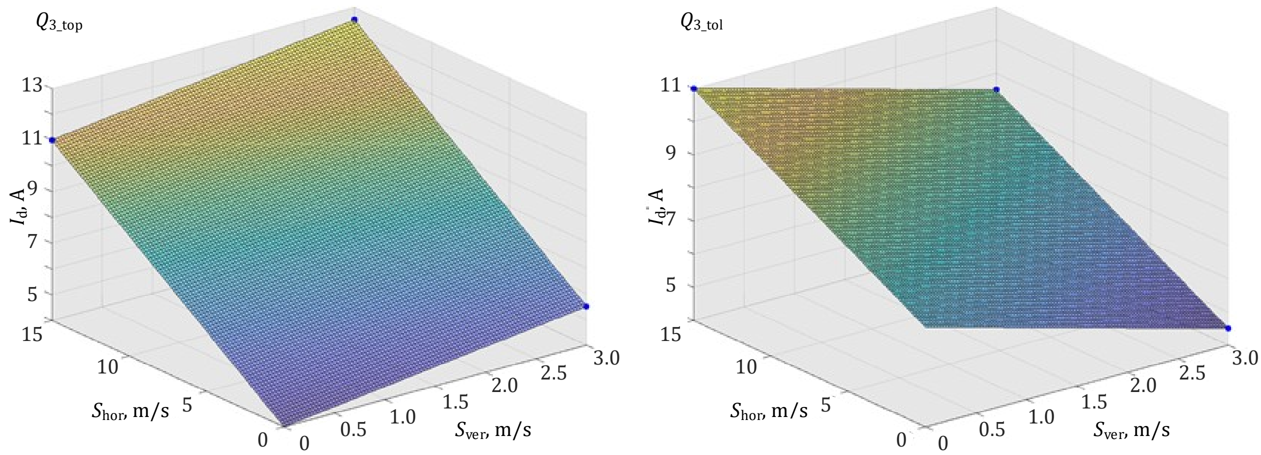
Fig. 4 – Colour map of simulation results for charge consumption for each flight mode

where m – number of observations; y_i – i-th response; β_k – k-th coefficient; β_0 – constant part in the model; x_{ij}– i-th observation of the j-th variable of the predictor (j=1,...,p), ε_i– i-th noise part, that is, a random error.

In our case, when the value I_d is predicted utilizing a linear equation of two parameters (speed), the equation (11) will be represented as follows:

$$I_d = a \cdot S_{ver} + b \cdot S_{hor} + c. \qquad (12)$$

where a and b define weights of S_{ver} and S_{hor} in the model, c - random error coefficient.



a) b)

Fig. 5 – Linear approximation of regression model, where blue dots are input data of I_d for calculation of Q_{3_top} (a) and Q_{3_tol} (b)

For development of the regression model, the reference data of current consumption from the Table 1 were used, and based on those data in MATLAB software the regression analysis was performed and regression coefficients were found (Table 2). The visualization of linear approximation of current consumption as well as reference data are shown in Fig. 5.

Table 2 – Coefficients of linear regression for current

Part of the flight trajectory	**a**	**b**	**c**
from (0; 0) to (x_D; y_D)	0,5	0,47	4
from (x_D; y_D) to (0; 0)	-0.83	0.27	7

The results of Q_{3_top} and Q_{3_tol} calculations are shown in Fig. 4c. The simulation results show that the acceptable values of $Q<Q_{lim}$ is observed for x_D =5000 m. At the same time, as can be seen from Fig. 4b, comparable results for the same x_D and y_D were obtained for the second flight profile. For further calculation, the 3rd flight profile was chosen which is explained by the optimal trajectory of the drone and lower consumption currents compared to the second flight scenario. So, after the selection of flight profile, number of drones, required for the continuous surveillance can be calculated.

Calculations of continuous surveillance system

According to the selected flight profile, the drone has a flight from the starting position – charging pad, to the observation point (x_D;y_D). There, the drone hovers and transmits the video to the command centre. Other drones are charged or waiting on charging pads. The available battery SOC of the drone at the observation point decreases in time, and at some time the drone sends the command for the flight of the next drone. The next drone will replace the previous because the SOC will drop to the minimal level, required for the return to the charging pad. A detailed flight profile, including changes of *x* and *y* coordinates of drones over time, battery current, and battery SOC, are shown in Fig. 6.

The start time T^{i}_{start} is determined for each *i* drone based on data on the flight time of the *i*-1 drone and is calculated according to the equation:

$$T_{start} = (i-1)\cdot\left(T_{lout} + T_{3_{tol}}\right), \quad (13)$$

where *i* - number of the drone in order of take-off, T_{lout} - available hovering time at observation point.

The time of arrival at the observation point T_{arr}, the time of submitting the command for the take-off of the drone *i*+1 T_{next}, the time of sending the *i*-th drone the command to return to charging pad T_{return}, the charging start time is calculated T_{start_ch}, time of finishing the charging T_{start_ch}, can be calculated by following equations:

$$T_{arr} = T_{start} + T_{3_{top}}, \quad (14)$$

$$T_{next} = T_{arr} + T_{lout}, \quad (15)$$

$$T_{return} = T_{3_{top}} + T_{next}, \quad (16)$$

$$T_{start_{ch}} = T_{return} + T_{3_{tol}}, \quad (17)$$

$$T_{end_{ch}} = T_{start_{ch}} + T_{ch}, \quad (18)$$

Charging time T_{ch} and time of hovering at observation point T_{lout} can be calculated as follows:

$$T_{ch} = \frac{Q - Q\cdot 0.2}{i_{ch}}\cdot 60, \quad (19)$$

$$T_{lout} = \frac{Q - Q_{3_{tol}} - Q_{3_{top}} - Q\cdot 0{,}2}{I_{loit}}\cdot 60, \quad (20)$$

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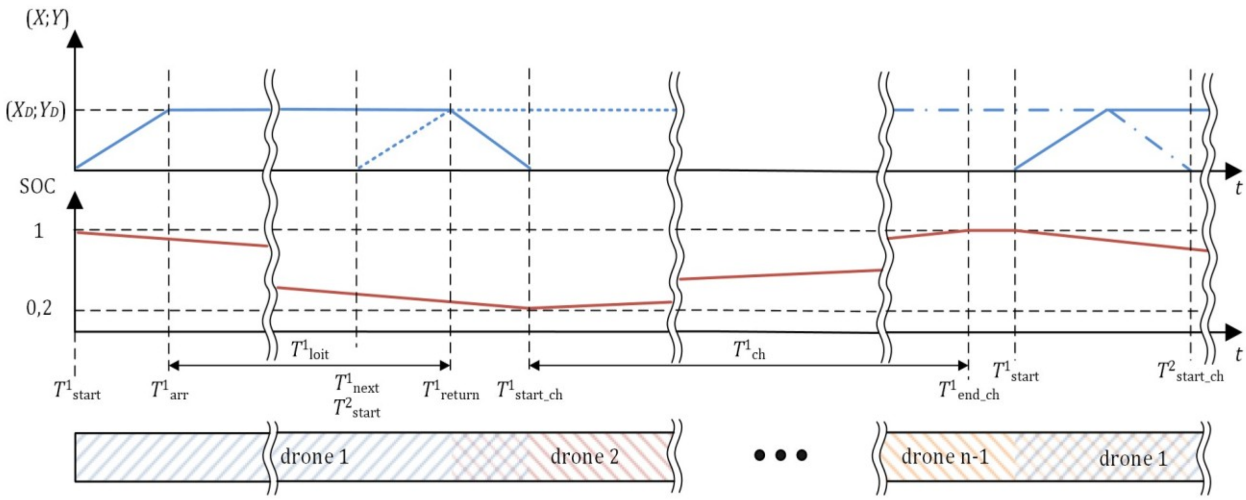

Fig. 6 – Detailed flight profile and continuous surveillance

System requirements and parameters

The following conditions and restrictions were used for the simulation of a continuous surveillance system:

- continuous surveillance is provided when at least one drone is hovering at the observation point;
- there can be only one drone in flight to point (x_D;y_D);
- all drones have the same battery parameters and battery status, the effect of battery aging is neglected;
- the current consumption of the drone depends only on the flight mode shown in Fig. 6, and is constant;
- transient processes when the consumption current changes and the effect of temperature are neglected;
- the charging process starts immediately after landing the drone at the starting position (0;0);
- drone i+1 takes-off immediately after receiving a command from drone i at time T_{next};
- vertical and horizontal speeds are limited at S_{v_lim} and S_{h_lim}.

The main parameters of the drone DJI Mavic 2 Enterprise that are used in the simulation, are shown in Table 3, data on current consumption are obtained from the regression analysis in the previous section.

Table 3 – The main parameters of the drone used in the study

Parameter name	Values
Battery capacity, Q_{bat}, A*h	3,85
Nominal battery voltage, V_{nom}, V	15,4
Charging current in CC mode, I_{CC}, A	4,53
Horizontal speed limit, $S_{hor\ lim}$, m/s	15
Vertical speed limit, $S_{ver\ lim}$, m/s	3

Maximum achievable flight range

To determine the maximum possible distance to the observing point that can be practically achieved x_{D_max}, the energy balance should be calculated. For hovering on observation point and safe returning to charging pad, the drone should have at least the charge Q_{com}, when arrived to observation point, that consist of three parts. The first one is Q_{3_tol} (charge consumption for the back flight), the second one is emergency reserve (in calculations $0{,}2Q_{bat}$ will be used), and the third one is charge consumption for hovering Q_{3_loit}. The value of Q_{com} and Q_{3_loit} be calculated as follows:

$$Q_{com} = Q_{3_{tol}} + 0{,}2 \cdot Q_{bat} + Q_{3_{loit}}, \qquad (21)$$

$$Q_{3_{loit}} = \frac{y_D}{S_{ver} \cdot 3600} \cdot I_{loit}. \qquad (22)$$

Taking into account that initial SOC is equal to 1, and is equivalent of Q_{bat}, all further calculations will be done in per unit (pu) values of SOC:

$$SOC_{top} = 1 - \frac{Q_{3_{top}}}{Q_{bat}}, \qquad (23)$$

$$SOC_{com} = \frac{Q_{com}}{Q}. \qquad (24)$$

In case, when the drone reaches the observing point, and the battery's SOC_{top} is more than SOC_{com}, the drone has enough energy for surveillance and a safe return home, in other words, $SOC_{top} \geq SOC_{com}$ must be fulfilled. Results of calculation of SOC_{top} and SOC_{com} surfaces as variation of x_D and y_D are shown in Fig. 7. Intersection of surfaces is a range of maximal achievable distance to observation point. As it can be seen, x_{Dmax} shows that the maximum possible observation distance is 6138 m.

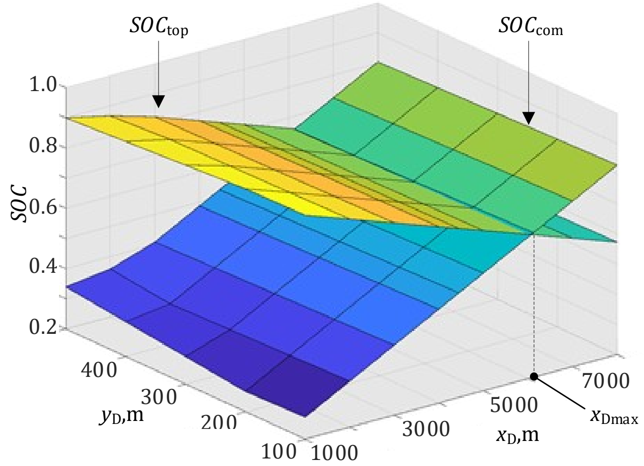

Fig. 7 – Results of SOC_{top} and SOC_{com} calculation

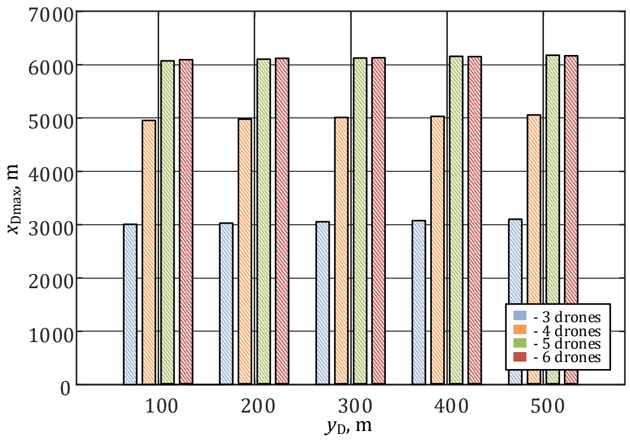

Fig. 8 – The result of continuous surveillance simulation

Effect of drones' number on continuous surveillance

For ensuring continuous surveillance in the first assumption, at least two drones for each observation point should be used – the first is hovering, and the second is charging, and then they are replaced by each other. The real number of drones will be more than two and will depend on the distance to the observation point, time, and speed of drone charging, current consumption during flight, etc. For further calculation, the drone battery model, presented in the study [18] was used to calculate the energy changes in the system, including the charging process and discharge during the flight. All numerical calculations were carried out in MATLAB software in the loop with a time step equal to 1 sec and the initial conditions SOC of all drones is 1. The drone battery model was used in m-script, which calculates the coordinates and operation mode (charging, waiting for flight, flight, hovering, sending the command for the next drone) for each drone according to the defined flight profile.

As a result of the calculation, the maximum distance to the observation point that still ensures continuous surveillance point for the number of drones n=2…6 and altitude y_D=100…500 m, was found. Results are summarized in Fig. 8, as it can be seen, the minimum number of drones for continuous surveillance is 3. This number can be used to provide constant surveillance at an up to 3084 meters distance. Changing the number of drones from 3 to 6 significantly increases the range to the observation point to 6138 meters.

According to mathematical calculations, a further increase in the number of drones will not lead to an increase in x_D, which cannot exceed the maximum achievable limit 6138 meters. An attempt to reach bigger x_D even with bigger number of drones will lead to the fact that drone i+1 should take-off at a time when drone i still has not yet reached the observation point.

Experimental validation and analysis of results

To verify the simulation result by taking into account such factors, as wind speed, real drone energy consumption, etc., the experimental verification was carried out in the study. A real DJI Mavic 2 Enterprise drone was used, and in total, 42 flights were carried out. These flights were done to check the relevance of the flight profile selection, the calculation of the current consumption, and the determination of the number of drones required for continuous surveillance at different altitudes and distances to the observation point. All tests were conducted in the period from March 1 to April 21, 2023. The main parameters of the drone are listed in Table 3.

Testing methodology

Indicators evaluated during the tests are the following: vertical speed, horizontal speed, flight time, state of SOC, and wind speed. Test conditions are given in Table 4.

The flights were conducted according to flight profiles 1 and 3, described in Chapter 2 of the paper, to determine the relevance of the preliminary calculations regarding the selection of the flight profile. According to the flight profile 3, the flights were conducted at a range of: 1000.

Table 4 – Test conditions of flights

Parameter	Value
Temperature, °C	2 … 18
Humidity, %	40 … 71
Wind speed, м/с	0.38 … 12.24
Dew point, °C	-5.5 … 6
Pressure, GPa	1007 … 1021

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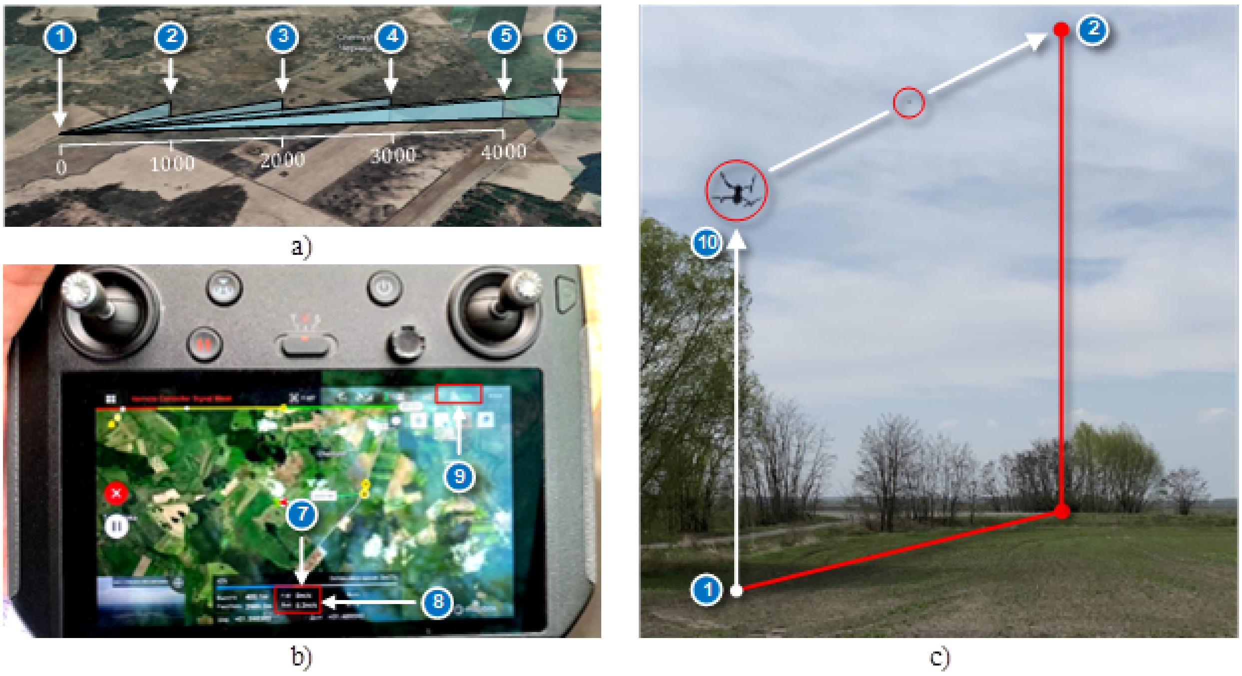

Fig. 9 – Experiment: (a) Flight route of the drone on Google Maps; (b) evaluated parameters on control panel; (c) photo of the drone flight path to the observation point according to the third flight profile; where 1 – launching site, 2…6 – observation points (1000, y_D), (2000, y_D), (3000, y_D), (4000, y_D), (4500, y_D), respectively, 7 – S_{ver}, 8 – S_{hor}, 9 – SOC, 10 – altitude of 10 m.

Due to compliance with flight safety, avoiding obstacles such as power lines and trees, flights according to the third scenario were conducted with a take-off to an altitude 10 meters from the starting position, and this point (0;10) was used as a starting point for the calculation. The battery discharge for take-off to the point (0;10) was not considered in the calculations. A photo of the trajectory of the take-off and subsequent flight is provided in Fig. 9c.

Hovering at the observation point was conducted for 60 seconds. If the drone's battery SOC after the flight to the observation point and back was enough for one more flight, this flight was performed, and the data was recorded and added to other results. All the flight parameters were obtained by monitoring the ground control station – the control panel (Fig. 9b) and analysing log files based on flight results through the Aidata.com application (Fig. 10).

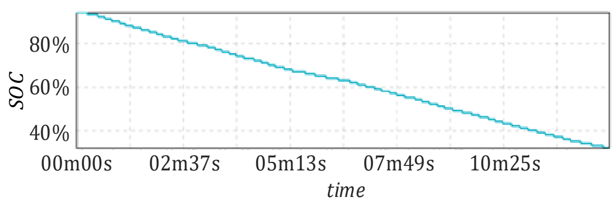

Fig. 10 – An example of a SOC change during time from log file data from Aidata.com

Test results and discussions

All test results are submitted to the open-data repository at [19]. The difference in the calculated values of the consumption current, which was calculated by linearization, and the actual obtained test flight data show that assumption of using S_{hor} and S_{ver} to determine the consumption current was correct (Fig. 11). It should be also noted, that some values obtained during test flights are significantly different from the calculated values, this may be due to external factors. To determine the influence of external factors, the wind speed at the point (x_D;y_D) was used (Fig. 11). This is an assumption that the faster the wind is, the higher the current consumption will be, but the effects of wind direction azimuth, wind gust speed, and flight azimuth are not considered. The obtained results show that an increase in wind speed up to 10 m/s and above significantly affects the battery discharge. At the same time, as can be seen, not all "peaks" of current consumption spikes are caused by high wind speed but some of them are rather caused by other factors.

To calculate updated values of Q_3 according to the results obtained during the tests, updated values of I_d was determined by using the linear regression analysis (equation 12). The results, showing the coefficients of linear regression (a, b, c) for current, are displayed in Table 5.

Table 5 – Regression analysis data

Flight trajectory	**a**	**b**	**c**
from (0;0) to (x_D;y_D)	0.69	0.22	6.70
from (x_D;y_D) to (0;0)	-1.34	0.20	9.90

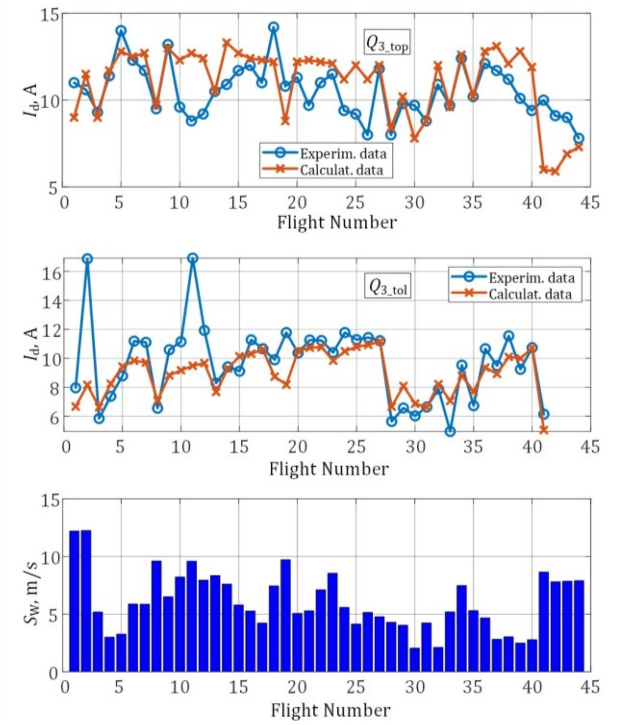

Fig. 11 – Comparison of the calculated and experiment current consumption for Q_{3top} and Q_{3tol} and wind speed at observation point (x_D,y_D) for 44 test flights

After performing calculations considering the consumption currents found in the experiment, we can see the difference between calculated of the maximum achievable distance to the observing point and the number of drones for "pure" and "updated by experiment" calculations (Fig. 12). As it can be seen, calculations, based on experimental verification of drone's current consumption, show shorter achievable distance to the observing point for all analysed altitudes y_D. The difference depends on number of used drones. Three drones were enough for continuous surveillance for "pure" calculation, but results, updated by experiment shows that such number is not enough, and continuous surveillance is not possible. With the increasing number of drones difference between two results became smaller: for n=4 difference is around 2100 m, for n=5 – around 1600 m, and for n=6 – around 700 m. Such influence of external factors should be taken into account for practical applications of drone's surveillance systems.

Conclusion

The optimal solution for surveillance of large critical infrastructure facilities, such as nuclear power plants or ammunition warehouses, dams etc., is the use of a group of drones, each of which can observe its own sector. For continuous surveillance, drones at the destination point should be replaced, when the battery state of charge drops close to the critical level, that necessary for returning to the charging pad. In this case one drone will hover in surveillance point, whereas other

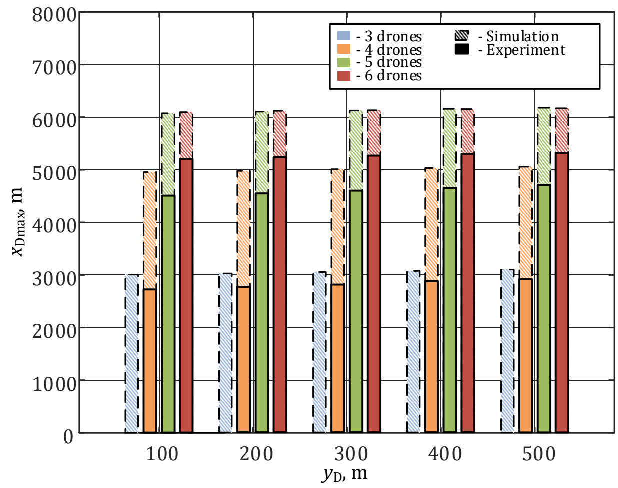

Fig. 12 – The result of continuous monitoring simulation considering experimental data

drones will be charged, or in their way from or to charging pads. To organize such surveillance in the most efficient way, the optimization of energy consumption of the drone, as well as the optimization of energy supply of charging station is required. Drone energy consumption during the flight and hovering depends on many controllable parameters, such as drone speed and load, as well as external parameters, such as wind direction and speed, ambient temperature, etc. To solve this issue, the mathematical model of drone energy consumption for three possible flight profiles was introduced in the paper. Based on the linear regression model for the prediction of drone's consumption and further simulation of proposed model for DJI Mavic 2 Enterprise drone in MATLAB software, the optimal flight profile, that provide the minimum energy consumption for the flight from charging to destination points was found. Further computer simulations were used to calculate the maximal possible distance between charging and destination points for continuous surveillance for altitude in range from 100 to 500 m and number of drones from 3 to 6. It was found, that for used for the simulation drone DJI Mavic 2 Enterprise, the maximal distance from charging to surveillance points cannot exceed the limit of 6138 meters. To verify developed models of surveillance system and results of simulation, experimental verification by 44 drone flights was carried out in the study. The flights were used to take into account the influence of external parameters, such as wind speed and direction on drone's energy consumption and obtain updated energy consumption model of the drone for continuous surveillance system. By the utilization of the model, updated by the results of experimental tests, it was found, that real maximal distance from charging to surveillance points is less than based on pure simulation model. The difference depends on the number of drones used for the surveillance system, and varies from around 2100 m for 4 drones to less than 1000 m for 6 drones.

The results, introduced in the study, are essential for the development of continuous surveillance systems

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based on drones. Based on the results, obtained in the study, it is possible to define the minimal number of drones that can ensure continuous surveillance, as the function from surveillance altitude and distance from charging to surveillance points. The results are verified on DJI Mavic 2 Enterprise drone, but they can be easily extended to any other drone by changing the initial parameters of the model (nominal current consumption, battery charge, etc.) and additional test flights for update of linear regression model.

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