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MULTI-AGENT UAV SYSTEM CONTROL FOR TRANSPORTING OVERSIZED PAYLOAD

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Abstract—The article solves the problem of transporting an oversized payload in space-constrained environments using a multi-agent unmanned aerial vehicle system. An adaptive hybrid control method combining relay (Bang-Bang) speed control at large suspension deflection angles and optimal linear-quadratic regulation (LQR) at small angles is synthesized. A mathematical model coupling payload pendulum dynamics, elastic cable tension, and quadcopter dynamics with force and energy constraints is proposed. To maintain group formation geometry and proportional tension distribution, a consensus protocol with hysteresis switching is integrated. The quality assessment of the multi-agent system is carried out by an integral indicator that includes mechanical stability, power consumption, and the angle of deflection of the payload to suppress pendulum oscillations for safe maneuvering in narrow spaces. Simulation in MATLAB for a group of 4 to 8 DJI M300 UAVs carrying a 20–30 kg payload along a parabolic trajectory demonstrated significant performance improvements. Compared to traditional PID and standalone LQR controllers, the proposed approach reduced settling time to 4.3 seconds, suppressed maximum overshoot to 3%, and lowered total energy consumption to 32 kJ. The proposed algorithm provides effective oscillation damping and dynamic cohesion, making it suitable for urban logistics, port infrastructure operations, and disaster recovery.

Keywords—Unmanned aerial vehicles, multi-agent systems; payload transportation; coordination; optimization; energy efficiency; oscillatory processes; mathematical modeling.

I. INTRODUCTION

Modern trends in the development of autonomous systems and robotics open up new opportunities for solving the problems of transporting complex payload. The use of multi-agent UAV systems for performing logistics operations in challenging conditions, where traditional means are ineffective or economically unfeasible, is becoming increasingly relevant.

Transportation of large-sized payload in environments with complex geometry (cities, ports, industrial zones) is accompanied by a number of restrictions caused by limited maneuvering space, the presence of static and dynamic obstacles, the need for precise positioning, and increased safety requirements.

Popular means of transportation, such as bridge and tower cranes, road transport (platforms, tractors), water transport, and air vehicles (helicopters), do not always provide the necessary flexibility and efficiency. They are characterized by limitations in operating costs, preparation time, and infrastructure availability. The typical problems of payload transportation for them include significant time costs, complexity of route planning, payload fluctuations, limited maneuverability, high energy costs, resource

queues, and dependence on the human factor. In addition, traditional solutions are not effective enough in cases of complex environmental geometry, when a quick response is required, particularly with limited access to infrastructure.

The purpose of this article is to develop a method for transporting large payload using a group of UAVs that minimizes vibrations, energy costs for transportation, and task completion time.

II. REVIEW OF LATEST ARTICLES

Researchers have solved payload transportation in various ways, but we are interested in tasks related to the interaction of robots, where the load-carrying capacity of one robot is insufficient, and therefore, other robots must be involved in solving this task. The primary issues that arise in this case are related to the stability of the work and the coordination of the robots' actions (see, for example, Kumar and Michael N. [1], Soon-Jo Chung et al. [2]). Within the framework of this task, Michael et al. [3] studied the problem of controlling several robots when transporting a payload fixed with cables to work out the appropriate configuration of the robots. Mellinger et al. [4] studied a similar problem, where the transportation was carried out by quadcopters, and

the control task was solved in the state space based on an approximate dynamic model, the parameters of which are specified in the process of experiments.

It is convenient to imagine a system of several robots as a multi-agent system and solve applied problems using such a system. And here, payload transportation can be solved by distributing the payload between autonomous robots. Then, the problems of autonomous navigation of each robot arise, the solution of which can be found in the work of Beard and McLain [5], which presents a solution to the problem of autonomous navigation, control, and monitoring of unmanned aerial vehicles during autonomous and semi-autonomous flight. Coordinated actions in a decentralized group can be achieved by introducing the concept of consensus proposed by Olfati-Saber et al. [6]. As part of the development of the theory of information consensus, Ren and Beard [7] proposed a solution to the problem of achieving consensus between several agents in conditions of limited and unreliable information exchange with dynamically changing interaction topologies.

Practical problems of payload transportation are presented in works [8] – [10], where experiments on the movement of three UAVs are presented by Bernard et al. [8], four quadcopters were considered by Cardona et al. [9], and Sharma and Sundaram [10] proposed a geometric approach to payload transportation control that does not require communication algorithms.

The initial requirements for the stability and coordination of agents in the transportation system require appropriate algorithms for tuning the controllers of the multi-agent system. For example, Sanalitro et al. [11] proposed a method for tuning the controller coefficients for a statically rigid suspended aerial manipulator using a minimum number of aerial robots and cables. TANG et al. [12] presented a strategy for controlling the configuration of multiple unmanned aerial vehicles (UAVs) within the framework of cooperative consensus, and a probabilistic model of target position uncertainty with UAV flight dynamics, camera properties, and a machine learning-based detection system was presented by Lanča et al. [13].

Khamis et al. [14] presented a review of current and promising approaches to the application of multi-worker systems with multiple resources.

From the point of view of information technology, the task of coordinated control of a group of UAVs requires processing of significant flows of telemetric data in real time. Information processing algorithms in UAV control systems, including signal filtering

and state assessment, are considered in [15]. The approach to constructing the trajectory of the UAV based on a mathematical model of motion, developed by the authors [16], ensures the correct integration of control algorithms with the kinematic equations of the system. The task of controlling a PID controller for a quadcopter and optimizing its parameters using digital filtering and genetic algorithms is investigated in [17], which is directly related to the synthesis of controllers for each agent of the group. Analysis of the effectiveness of information systems for inventory management and logistics [18] confirms the relevance of complex evaluation criteria for systems of this class.

Analysis of the presented sources indicates the relevance of using multi-agent systems for transporting large-sized payload in difficult building conditions.

III. PROBLEM STATEMENT

The problem of transporting large-sized payload by a multi-agent UAV system with a suspension fixed by rigid cables is considered, which is formulated as follows: a group of N UAVs transports payload with a mass M on a route section characterized by the initial p^{start} and final p^{end} points, $p^{\text{start}} \in R^3$, and $p^{\text{end}} \in R^3$.

The load mass M is such that it exceeds the load-lifting capacity of one UAV, i.e. $M > m_{\text{max}}$, m_{max} is the maximum load mass that one UAV is capable of lifting.

The dynamics of the load is described by the equation

$$M\ddot{x}_L = \sum_{i=1}^N T_i q_i - Mge_3. \quad (1)$$

In equation (1) x_L is its Cartesian coordinates, $x_L \in R^3$, T_i is the cable tension; q_i is the unit vector of the cable, $q_i \in S^2$, g is the acceleration of gravity, $g \approx 9.82 \text{ m/s}^2$, $e_3 = [0 \ 0 \ 1]^T$ is the unit vector of the vertical axis.

Due to control actions aimed at compensating for the arising suspension oscillations and disturbances, the suspension has its own dynamics in the angular coordinate system, which is described by the differential equation

$$\ddot{\theta} + \frac{g}{l} \sin \theta = F(T_i, x_L), \quad (2)$$

where θ is the vector of the cable deflection angles from the vertical; l is the length of the cables, cables without stretching, of the same length; $F(T_i, x_L)$ is the generalized nonlinear effect of cable tension and spatial movement of the load on the angular

dynamics of the suspension. Equation (2) corresponds to the equation of pendulum oscillations; at small deflection angles, a linearized pendulum model is used.

The dynamics of each UAV is described by a differential equation of the form

$$m_i \ddot{x}_i = f_i R_i e_3 - m_i g e_3 - T_i q_i + d_i. \quad (3)$$

In equation (3) the following notations are introduced: m_i is the mass of the i -th UAV; x_i is the position of the i -th UAV, $x_i \in R^3$; f_i is the UAV thrust; R_i is the UAV orientation matrix, $R_i \in SO(3)$; d_i is the disturbance.

There is a strict relationship between the coordinates of the UAV and the payload, which is established by the equation

$$x_i = x_L + l_i q_i. \quad (4)$$

The UAV's thrust is subject to a limitation

$$f_i^{\min} \leq f_i \leq f_i^{\max}, \quad (5)$$

where $f_i^{\min}$ and $f_i^{\max}$ are the minimum and maximum values of traction forces.

Payload transportation is carried out by all UAVs, which can be fixed by the tension of the cables, which can correspond to inequality

$$T_{\min} < T_i < T_{\max}, \quad (6)$$

provided that the cables do not sag, i.e. $T_i > 0$ and taking into account the sufficiency of the UAV energy for the assigned task, which is expressed by the inequality

$$\int_0^T P_i(t) dt \leq E_i^{\max}, \quad (7)$$

where $E_i^{\max}$ is the maximum energy consumption of the i -th UAV for time T , $P_i(t)$ is the instantaneous power of the UAV,

$$P_i = (f_i R_i e_3)^T \dot{x}_i. \quad (8)$$

In equation (8), the value $f_i R_i e_3$ determines the control influence of the i -th UAV.

Transportation is considered successful if group cohesion and payload stability are maintained, which is sensitive to the tension of the cables T_i , is ensured, energy costs do not exceed the permissible energy resources of the UAV, and angular oscillations of the suspension do not affect the dynamic characteristics of an individual UAV, which can be given by a generalized efficiency criterion in the form

$$J = \alpha \sum_{i=1}^N \int_0^T T_i^2 dt + \beta \sum_{i=1}^N \int_0^T P_i^2 dt + \gamma \int_0^T \theta^2 dt \rightarrow \min. \quad (9)$$

where α , β and γ are the matching coefficients. The choice of coefficients of functional (9) determines the balance between three competing goals: minimization of cable tension (system reliability), minimization of energy consumption (flight autonomy), and minimization of oscillations (transportation quality). In real-world applications, it is recommended to perform parametric optimization of α , β , γ based on the priorities of a specific mission.

The choice of an integral quality functional in the form of a sum of three quadratic components is due to the need to achieve a compromise between three conflicting physical and technical requirements for the "UAV group – payload" system:

1) The first term ($\alpha \sum_{i=1}^N \int_0^T T_i^2 dt$) is responsible for the reliability of the coupling and mechanical strength. The quadratic estimate of the cable tension forces T_i minimizes the peak mechanical loads on the cargo fastening elements and the quadrocopter frame. The use of the quadratic form minimizes the dispersion of forces between the agents, which prevents both critical overloads of individual cables (which can lead to their rupture) and their sagging ($T_i < T_{\min}$), which causes a loss of controllability of the system.

2) The second term ($\beta \sum_{i=1}^N \int_0^T P_i^2 dt$) is responsible for the energy efficiency and flight duration. The instantaneous power of the UAV P_i is proportional to the discharge rate of the batteries (or energy consumption). Minimizing the integral of the square of the power minimizes the total energy consumption of the group to perform the mission, expanding the range and increasing the useful operating time of the UAV. In addition, minimizing P_i^2 prevents sharp current surges in the power plants.

3) The third term ($\gamma \sum_{i=1}^N \int_0^T \theta^2 dt$) is responsible for positioning accuracy and transportation safety. The suspension deflection angle θ characterizes the pendulum oscillations of the load. Its square integral is a measure of the dynamic accuracy of the system. Damping oscillations $\theta \rightarrow 0$ is critical when moving in a confined space (between buildings, cranes, infrastructure elements) to prevent collisions and the occurrence of uncontrolled swings, which are transferred to the UAVs themselves.

The weighting factors are normalized by the condition $\alpha + \beta + \gamma = 1$ and determine the priority of the corresponding subcriteria depending on the specifics of the flight task. In the conditions of the

transportation problem in a limited space, the priority is chosen to be the damping of oscillations (transportation quality), therefore the value $\gamma = 0.5$ is taken, while the load uniformity and energy efficiency have the same distributed weights $\alpha = \beta = 0.25$. The quadratic form of the functional is consistent with the classical theory of linear-quadratic optimal control (LQR), which guarantees the existence of a unique and stable solution to the optimization problem.

The task is to synthesize control actions for each UAV that ensure payload transportation along a given trajectory and minimize the functional (9) taking into account payload dynamics (1), angular dynamics of the suspension (2), UAV dynamics (3), as well as constraints on traction forces (5), cable tension (6), and UAV energy resources (7).

IV. PROPOSED METHOD

The dynamics of a single UAV in a system with a suspension in a vertical plane during takeoff or landing is considered. Changes in coordinates lead to suspension oscillations, which can be in a wide range. In this case, it is advisable to propose an adaptive hybrid system that recognizes the angles of suspension deviation and quickly damps suspension oscillations by applying different approaches to control signal synthesis [19], [20]. For control synthesis, the problem is decomposed into planar subproblems.

Thus, at large angles, control should lead to minimal errors in minimal time, and at small errors, the optimal error is achieved, which can be represented as

$$u_i = \begin{cases} u_{i1}, & \text{if } |\theta| \geq \theta_{act} \\ u_{i2}, & \text{otherwise,} \end{cases} \quad (10)$$

where

$$u_{i1} = \begin{cases} U, & \text{if } F(M, \theta) \geq 0, \\ -U, & \text{otherwise,} \end{cases} \quad (11)$$

In equation (11) $U = \max_{t \leq t_1} |u_{i1}(t)|$, $t_0 \leq t \leq t_1$,

$[t_0, t] \subset T$ is the duration of the control signal $u_{i1}(t)$, $F(M, \theta)$ is the switching function of the control signal $\{U, -U\}$, which has the form

$$F(M, \theta) = -\theta_1 - \frac{M}{2} \theta_2 |\theta_2|. \quad (12)$$

In equation (12), the coordinates θ_1 and θ_2 are associated with the measured initial coordinate and its rate of change, i.e.

$$\theta_1 = \theta, \quad \theta_2 = \dot{\theta}. \quad (13)$$

The control u_2 has the form of feedback on the coordinate vector X , which is written as

$$u_{i2} = -KX_i, \quad (14)$$

$$K = R^{-1}B^T P, \quad (15)$$

where P is the matrix corresponding to the solution of the matrix algebraic Riccati equation; B is the input matrix in the matrix form of model (3). When calculating the controller (14), (15) in model (2), the substitution $\sin \theta \approx \theta$ is used.

The state vector of a single UAV in (14) and the suspension in a planar decomposition is taken as $X = [\theta_1, \theta_2, x_i, dx_i/dt]^T$, where θ is the cable deflection angle, θ_2 is the angular velocity, $x_i, dx_i/dt$ are the position and velocity of the i -th UAV.

The input matrix B in model (3), (15) is formed based on the physical characteristics of the quadcopter: $B = [0, 1/m_i l, 0, 1/m_i]^T$, where m_i is the mass of the UAV, l is the length of the cable.

Control (14) ensures the minimization of the quadratic functional

$$J_1 = \int_{t_1}^T (E^T Q E + u_{i2}^T R u_{i2}) dt. \quad (16)$$

In equation (16) Q, R are weight matrices that determine the contribution of each term to achieving the required effect in control quality. The weight matrix $Q = \text{diag}(q_{\theta 1}, q_{\theta 2}, q_x, q_{dx/dt})$ in functional (16) is chosen with the priority of damping oscillations: $q_{\theta} \gg q_x$ (which corresponds to the specification (22) – (23)).

E is a vector containing the control error content

$$E = X - X_{\text{ref}}. \quad (17)$$

In equation (17) X_{ref} is a vector that specifies the desired trajectory of the transport group. At small angles of deviation θ , the control u_{i2} is synthesized based on the LQR approach, which provides local minimization of the functional (16), which is a partial case of the generalized criterion (9).

In the presence of disturbances d_i , a hysteresis type shift is introduced into the vector of measuring coordinates θ' of the switching function (12)

$$\theta'_i = \begin{cases} \theta_i - \Delta_i, & \text{if } F(M, \theta) \geq 0, \\ \theta_i + \Delta_i, & \text{otherwise.} \end{cases} \quad (18)$$

In equation (18) Δ_i is the hysteresis zone.

Control signals u_i affect the values of traction forces f_i in equation (3), which, through the tension

of the cables T_i , forms the dynamics of the load (1) and the angular dynamics of the suspension (2).

To ensure group transportation, coordinated UAV control is formed in the form of

$$u_i = u_i^{\text{loc}} + u_i^{\text{coop}}, \quad (19)$$

which supports the given configuration of the group and the required distribution of cable tension between agents. In equation (19) u_i^{loc} is the control component that specifies the stabilization of the position of an individual UAV in the group and u_i^{coop} is the component that ensures the coordinated movement of the group [21],

$$u_i^{\text{coop}} = \sum_{j \in N_i} a_{ij} (x_j - x_i). \quad (20)$$

In equation (20) N_i is the set of neighbors, a_{ij} are the matching coefficients.

Thus, the proposed control system implements a hybrid control principle, in which relay high-speed control is used at large angles of deviation, and at small angles, optimal LQR control is used, which ensures stabilization of the suspension and coordinated transportation of payload by a group of UAVs.

In real transportation conditions, a group of UAVs is exposed to external disturbances $d_i(t)$ (wind load, turbulence, aerodynamic wake), which act unevenly on each agent. This creates a threat of movement desynchronization, violation of the group geometry, and the occurrence of dangerous parasitic oscillations of the cargo.

To compensate for these factors, the developed system implements double parrying:

1) Local compensation of disturbances at the level of an individual agent. To prevent high-frequency false switching of control channels under conditions of external disturbances d_i , a hysteresis zone Δ (18) is introduced into the switching function (12). It adapts the operating limits of the relay mode according to the maximum expected disturbances $\max |d_i(t)|$, which ensures the robustness of the local stabilization of each UAV.

2) Spatial consensus synchronization protocol: To maintain the unity of group actions under the uneven influence of control disturbances (19) contains a cooperative term u_i^{coop} (20). The consensus algorithm calculates the coordinate variance between neighbors $\sum_{j \in N_i} a_{ij} (x_i - x_j)$ and adjusts the thrust of each UAV f_i in real time. This ensures that even if one of the UAVs experiences a local wind gust d_i , the other agents adapt their motion, preserving the

mutual location Δx_{ij} , the cable tension T_i , and preventing payload skew.

Step-by-step algorithm for the operation of a hybrid regulator:

Step 1 (Telemetry collection). The input data at each time point t are the deflection angle $\theta(t)$, angular velocity $d\theta(t)$, and current coordinates $x_i(t)$ measured by sensors (IMU, optical sensors, GPS).

Step 2 (Checking switching conditions). The value of the switching function (12) is calculated.

- If $|\theta(t)| > \theta_{\text{act}} + \Delta$ (where $\theta_{\text{act}} = \theta_{\text{perm}}^\circ$, Δ is the hysteresis zone), the system switches to Mode 1 (Relay / Bang-Bang). The maximized thrust control $u_i = -U \text{sign}(F)$ is formed to reduce the amplitude as quickly as possible.

- Otherwise, the system enters Mode 2 (LQR). The control is calculated as (14), (15).

Step 3 (Group synchronization). To the formed local control u_i , a cooperative consensus term (20) is added, which adjusts the thrust of the engines f_i to maintain the rigid geometry of the formation.

Step 4 (Command issuance). The resulting thrust limit signal $f_i \in [f_{\min}, f_{\max}]$ is fed to the ESCs of each unmanned platform.

V. SIMULATION

The problem of transporting a payload with a mass of $M = 20\text{--}30$ kg by a group of UAVs consisting of $N = 4\text{--}8$ vehicles is considered. The payload is secured with cables $l = 1\text{--}3$ m.

The load placed on the surface at a point with coordinate $p^{\text{start}} = 0$ moves to point $p^{\text{end}} = 50$ in the vertical plane along the horizontal coordinate $x \in [0, 50]$ m along a parabolic trajectory in the form

$$z(x) = -0.01x^2 + 0.5x. \quad (21)$$

In this case, the maximum vertical coordinate of the payload lifting point does not exceed $z_L = 6.25$ m.

For movement, DJI M300 type UAVs with a mass $m = 9$ kg, taking into account the mass of the batteries, with traction forces in the range of $50N f_i \leq 125N$ are used.

The cable must withstand $T_i^{\text{max}} \leq T_i^{\text{allow}}$, where $T_i^{\text{allow}} = kT_i^{\text{work}}$, and the permissible cable load must exceed the working tension by $k = 2\text{--}3$ times.

The time t of payload transportation under the task conditions should not exceed $T_{\text{max}} \leq 25$ s, which allows us to set $E_i^{\text{max}} = 5 \times 10^4$ J.

Considering that oscillations are the most important component of functional (9), we set the coefficients $\alpha = \beta = 0.25$ and $\gamma = 0.5$.

The parameter θ_{act} in the control law (10) is equal to 3 degrees.

Let the matrix Q in functional (16) be chosen so as to penalize larger angles more, namely

$$Q = \begin{bmatrix} 10 & 0 \\ 0 & 1 \end{bmatrix} \quad (22)$$

and

$$R = [1]. \quad (23)$$

The hysteresis zone Δ_i to prevent high-frequency switching must be consistent with the maximum level of disturbances, in the simulation it is set equal to $\Delta_i = 1.2a_i^{max}$.

For the simulation, a fully connected topology of agent interaction with coefficients $a_{ij} = 1$ is used.

The simulation results are presented in Figs 1–4. Figures 1 and 2 show the dependences of the coordinates $\theta, \dot{\theta}$ in the phase plane and in the time plane, respectively. The graphs allow us to track the transition of the system from the relay control zone to the asymptotic stabilization region, which is provided by the LQR regulator.

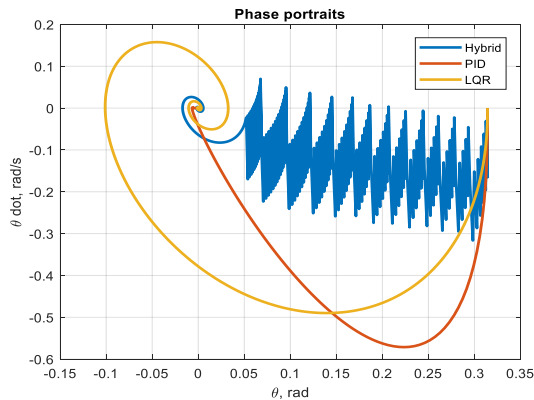


Fig. 1. Load control graph in the phase plane of coordinates $\theta, \dot{\theta}$

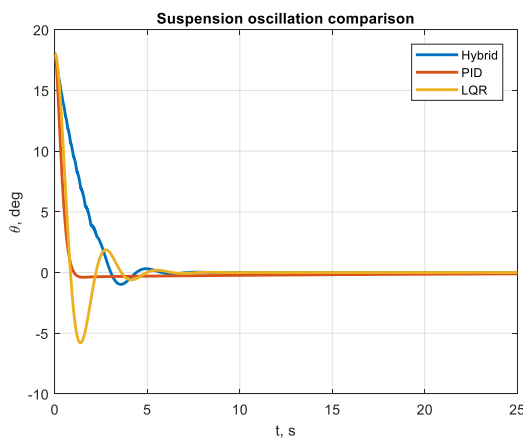


Fig. 2. Graph of dependence $\theta(t)$

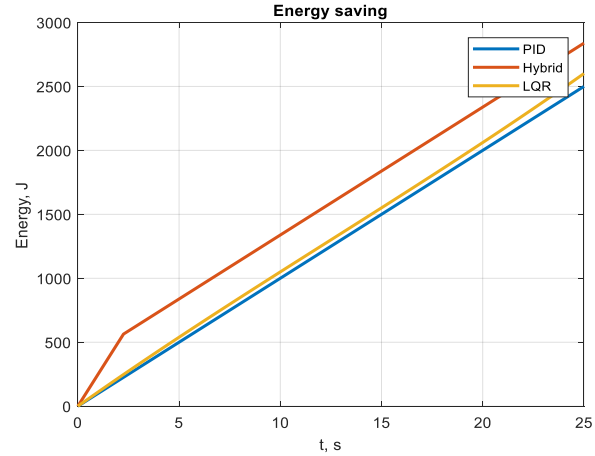


Fig. 3. Energy consumption graphs for PID controller and hybrid approach

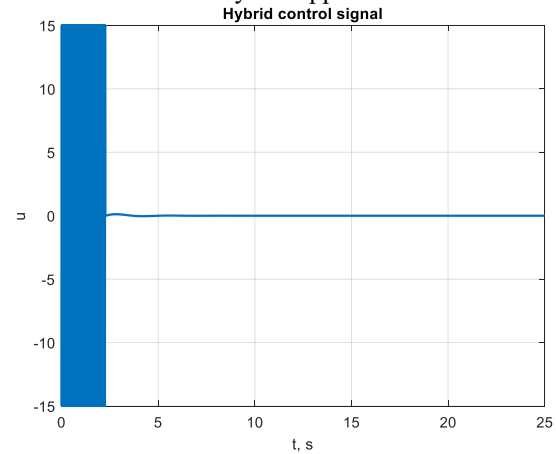


Fig. 4. Graph $u(t)$ in hybrid control

A comparison of the energy efficiency of the integrated power consumption of the traditional PID controller and the proposed hybrid approach is presented in Fig. 3.

The comparison of the integrated power consumption shows that the hybrid approach provides lower power consumption compared to the PID controller and better performance compared to pure LQR control. This is explained by the use of relay mode at large deflection angles and optimal LQR control near the equilibrium position.

VI. DISCUSSION OF RESULTS

A comparison of the proposed approach according to application criteria with existing tools and management quality indicators of common types of regulators is presented in Tables I and II, respectively, which allows us to establish its main advantages. The simulation results show that the proposed hybrid approach provides faster damping of suspension oscillations compared to PID and LQR controllers. The relay component provides fast response at large deflection angles, while the LQR controller

guarantees asymptotic stabilization near the equilibrium position. This allows to reduce the integral oscillation index and energy consumption of the system.

TABLE I. COMPARISON OF UAV GROUP TRANSPORTATION WITH KNOWN MEANS

Criterion	Traditional remedies	UAVs group
Time	Long	Short
Flexibility	Low	High
Cost	High	Moderate
Autonomy	Low	High

TABLE II. REGULATOR COMPARISON

Indicator	PID	LQR	HYBRID
Fluctuation	Smooth	Significant	Moderate
Precision	Permissible	Highest in asymptotics	Highest in asymptotics
Settling time, s	8.2	10.1	4.3
Overshoot, %	18	9	3
Energy, kJ	41	38	32

IV. CONCLUSIONS

The article investigates the problem of transporting an oversized payload, the weight of which exceeds the payload lifting capacity of an individual UAV, by a multi-agent system, whose agents, in addition to the target task of transportation to the destination, interact to overcome suspension oscillations, which complicates the target task.

The problem is solved by taking into account the dynamics of the group intended for transportation and the dynamics of the suspension, which is represented by the differential equation of a pendulum. There are kinematic relationships between the payload, which is fed by a material point, and the agents of the group, which are taken into account when finding the control influences on a given route. To assess the quality of UAV transportation of such payload, an integral quality function is introduced, which takes into account the limitations on thrust, the energy capabilities of the UAV, and the oscillations of the payload.

The task of finding control influences is based on a hybrid solution, when at large angles of deviation of the cable from the vertical, optimal control by speed is applied, and small deviations of angles are countered by optimal control by a linear-quadratic problem. This approach allows us to present a control system as a hybrid adaptive one, the switching of channels of which is carried out according to the rule

of confirming the angle going beyond the accepted small value Δ to exclude false switching.

The developed UAV coordination algorithm, which is based on the consensus rule, has high final system performance that satisfies the specified integral system efficiency criterion. The proposed payload transportation approach can be useful in densely populated areas, which include port logistics and debris clearance in global disaster areas.

Future research is planned to focus on taking into account wind loads on the UAS-payload system, applying artificial intelligence to optimize the system, scaling the system, and conducting experiments in real conditions.

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Д. П. Кучеров, М. С. Граф. Керування багатоагентною системою БПЛА під час транспортування великогабаритного вантажу

У статті розв'язано задачу транспортування великогабаритного вантажу в обмеженому просторі за допомогою багатоагентної системи безпілотних літальних апаратів. Синтезовано метод адаптивного гібридного керування, що поєднує релейний режим за швидкістю при великих кутах відхилення підвісу та лінійно-квадратичний регулятор (LQR) при малих кутах. Запропоновано математичну модель, яка враховує маятникову динаміку вантажу, натяг тросів, динаміку квадрокоптерів і обмеження на тягу та енергоресурси. Для збереження геометрії групи та розподілу навантаження інтегровано децентралізований протокол консенсусу з гістерезисним перемиканням. Оцінювання якості багатоагентної системи проводиться інтегральним показником, який включає механічну стійкість, споживання електроенергії та кут відхилення корисного навантаження для придушення коливань маятника для безпечного маневрування у вузьких просторах. Моделювання в середовищі MATLAB для групи з 4–8 БПЛА типу DJI M300 із вантажем 20–30 кг на параболічній траєкторії підтвердило високу ефективність підходу. Порівняно з PID та LQR регуляторами, запропонований підхід скоротив час перехідного процесу до 4.3 с, зменшив перерегулювання до 3% та знизив енерговитрати до 32 кДж. Метод забезпечує ефективне гасіння коливань і стабільність групи, що є актуальним для міської логістики, портової інфраструктури та розбору завалів.

Ключові слова: безпілотні літальні апарати, багатоагентні системи, транспортування вантажів, координація, оптимізація, енергетична ефективність, коливальні процеси, математичне моделювання.

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