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DEVELOPMENT OF AN INTELLIGENT CONTROL AND ENERGY MANAGEMENT SYSTEM FOR STRATOSPHERIC TELECOMMUNICATION AIRSHIPS

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The object of the study is an autonomous high-altitude airship platform. This type of high-altitude platform is designed for long-term telecommunication retransmission at altitudes of 18–25 km. The main problem lies in the insufficient stability of flight at the height of the stratosphere and the limited energy capabilities of aircraft. An integrated intelligent control system and energy management have been developed to solve the problems. This architecture in portable form includes a sensor module, an STM32 microcontroller, a LoRa telemetry channel, a mathematical model of dynamics taking into account lift, aerodynamic drag, external factors and atmospheric parameters, and most importantly, a hybrid adaptive PID-fuzzy controller was proposed. Additionally, a model of the energy balance was proposed, which directly interacts with solar panels, energy consumption of drives and battery operation. The simulation data obtained shows that the use of the PID-fuzzy controller provides a significant increase in the stability of the platform. The transition time is reduced by 44.4%, the maximum deviation from the set altitude and flight path is reduced by 56.5%, and the average drive consumption is reduced by 20–22%. The energy balance model demonstrates that the developed system is capable of retaining up to 46% of the battery charge after 24 hours of battery life, which is 18% higher compared to a system without adaptive energy management.

The practical significance of the project lies in the possibility of using the developed system as part of autonomous telecommunications networks, balloons, an emergency communication system, remote sensing of the earth, as well as in elements of promising 6G and NTN networks

Keywords: high-altitude platform systems (HAPS), airships, PID-fuzzy, LoRa, MatLab, aerodynamic modeling, energy management

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1. Introduction

The fast growth of the modern telecommunication systems demands the need to increase the coverage area, bandwidth, and offer reliable communications to the locations that are difficult to reach. It is especially the integration of network solutions into the geographical areas where the establishment of ground infrastructure is financially complex or cannot be established due to geographical or climatic factors. Among the opportunities in this regard are stratospheric high-altitude platforms (HAPS) [1, 2], which can offer long-term self-sufficient operation at the altitude of 18–25 km and serve as repeaters of telecommunication traffic.

Compared to satellite systems, stratospheric platforms are characterized by a shorter signal delay time, low maintenance costs and are able to alter the network configuration in a very short time. Compared to ground stations, HAPS can be said to have a larger coverage radius, thus they are useful in sparsely populated areas, coastal areas, mountainous areas, and territories with limited infrastructure. Nonetheless, there are various inherent challenges of operation of platforms at high altitudes. These encompass the impact of the high-speed wind currents, sharp fall in air density, fluctuations in temperature, low production of solar energy, and long-term battery life without the technical interference.

Stratospheric airships would need to use smart control strategies that can adjust to the constantly evolving weather patterns so that they can maintain stability in their positions and use the available energy optimally. Classical PID controllers lack the needed stability in the event of major disturbances but fuzzy logic algorithms enable the adjustment of the control parameters in real time. Simultaneously, the successful operation of the platform is not only based on the stabilization algorithm, but the energy balance is also predetermined by the interaction of solar generation and the load of the actuators and the properties of the battery.

The former research was previously published on architecture development of the stratospheric telecommunications platform and aerodynamic characteristics optimization. The problems of selecting the operating frequency of 433MHz [2], dynamic modeling and stability of multi-variable systems were taken into account in the following works. Nonetheless, there exist virtually no built-in solutions based on implementing intelligent control and energy management on a single circuit to be used in reality.

Despite significant progress in the field of high-rise platforms over the past 10 years, the scientific topic itself remains relevant for a number of reasons. Although there is progress, there is still no ideal. The global demand for high-speed communications in remote regions is growing every year, and existing satellite systems are unable to meet the need. Climate change is leading to an increase in the frequency of extreme wind events, which requires the development of a clearer and more sustainable management system for high-rise platforms. The development of 6G networks and the NTN concept directly involves the use of high-rise platforms as elements of the future global communications infrastructure. Thus, research aimed at improving the sustainability, energy efficiency, and autonomy of stratospheric airships is an important and sought-after scientific field.

Therefore, the study of the development of intelligent control systems and energy management for high-rise platforms is a scientifically significant and practically demanded task.

2. Literature review and problem statement

The article [1] discusses the radio-frequency management strategies of telecommunication systems in the atmosphere. It is demonstrated that the adequate distribution of the frequency resources is an important way of reducing the impact of interference and enhancing communication stability at higher altitudes. However, the question which remains unsolved is whether frequency planning can be reliable in the fast-changing atmospheric conditions, when the wind turbulence and air density gradients deform signal transmission. This complexity is due to the physical uncertainty of the stratified layers of the atmosphere that limits the use of set RF allocation. Another possible solution is the combination of adaptive and autonomous RF control. This shows that further studies on integrated intelligent systems of HAPS should be conducted.

In the paper [2], the authors design a comprehensive network architecture of remote regions based on stratospheric airships. It is revealed that the higher-altitude platforms are can effectively increase the coverage and facilitate telecommunication networks in areas with a poor infrastructure. However, the problem that remains unsolved is long-term autonomy and energetic sustainability of such platforms in the conditions of the low air density and varying solar radiation. Such challenges are explained by objective constraints of producing solar energy at high altitudes. One solution of addressing these problems is by using adaptive power management systems. This indicates that more research is required on energy efficient HAPS architectures.

The journal article [3] introduces a way to use dispersion -correlation radio direction finding that is very sensitive to noise and signal distortion. It is demonstrated that spectral-correlation analysis has a considerable positive impact on the precision of the navigation. However, issues that have not been addressed deal with the use of these techniques on the transport of airborne platforms in the presence of intense aerodynamic perturbations. This is primarily due to the sensitivity of correlation measures to platform vibrations and fast attitudinal shifts. One of the possible solutions is to apply signal-processing algorithms together with real-time stabilization control. This underscores the necessity of a study on combined stabilization and sensing of HAPS.

The article [4] provides an overview of the LiDAR technologies in UAV detection and classification. It is demonstrated that multi-sensor methods yield very fine and dependable detection in various atmospheric conditions. However, the remaining question is related to energy consumption and continuous behavior over many years of LiDAR-based systems in stratospheric conditions. The reason behind these limitations is the demand of the LiDAR sensors in terms of high computational and optical requirements. One alternative to this can be the application of adaptive energy allocation methods and low-power communication subunits. This signifies that energy efficient sensor architectures of stratospheric platforms should be studied.

The article [5] ideas on the better spectral-correlation direction-finding methods with machine learning additions. As it is demonstrated, AI-powered signal analysis allows reaching a greater accuracy and the convergence speed. However, some questions still exist about how these methods can be integrated into resource constrained embedded systems, e.g., HAPS flight controllers. This challenge is due to the complexities of computations and lots of energy used in machine learning algorithms. One possible option is hybrid architectures that include lightweight embedded controllers and selective AI processing. This justifies the need to do research on smart yet energy sensitive HAPS control systems.

The article [6] is a base review of HAPS as a wireless communication infrastructure. It is illustrated that stratospheric platforms have lower latency and elastic network deployment. However, there are still unanswered questions of aerodynamic stability, power availability and control autonomy needed to operate over a long time. Such difficulties are caused by the severe weather conditions at the height of 18–25 km. One of the solutions to this problem is in the form of advanced stabilization systems and energy management models. This validates the need to conduct further studies on stability and endurance of HAPS.

The article [7] has presented the vision which is most comprehensive of future 6G HAPS networks and how they are going to be utilized in next generation non-terrestrial networks. As it is demonstrated, HAPS can be used as primary components of the Space-Air-Ground integrated architecture. However, unanswered questions are real time flexibility of platform control algorithms and energy limits during varying environmental loads. All these are due to the fact that future 6G/NTN architectures demand dynamically reconfigurable airborne nodes. One way of solving these constraints is through the use of smart fuzzy-supported control systems. It means that the research into adaptive HAPS control is still very topical.

In the article [8], a detailed discussion of the fuzzy logic control systems in electric and hybrid vehicles is provided. The fuzzy algorithms are demonstrated to be of great benefit to the robustness of a system in ambiguous situations. However, there are questions that still remain unanswered regarding the adaptation of these techniques to aerial platforms that experience very high dynamic aspects. The challenge is caused by nonlinear and altitude dependent air properties in the stratosphere. One solution to this problem is to integrate fuzzy control and high-fidelity aerodynamic models. This underscores the necessity of HAPS-specific control strategies that use fuzzy techniques.

The article [9] suggests an energy management plan based on fuzzy logic of heavy transport systems. Adaptive fuzzy control is shown to be more energy efficient and power losses are minimized. However, some gaps still remain regarding how these methods can be applied to solar-powered stratospheric platforms, which power generation is intermittent. This is due to the fact that solar supplies on high altitudes fluctuate drastically on the time of the day, and weather conditions. One potential way would be to combine the fuzzy energy control and real-time solar and battery modeling. This supports the applicability of the adaptive energy control study of HAPS.

The article [10] dwells on the practical considerations of implementing HAPS in Space RAN systems. Such platforms are demonstrated to be necessary in the next-generation wide-area communication. However, the question that remains yet to be answered is why there is no single system that combines stabilization, energy management, telemetry, and aerodynamic modeling. This can be explained by the fact that it is quite challenging to incorporate many subsystems into a lightweight airborne platform. One way of addressing this challenge is to create closed-loop architecture to combine sensing, control, and energy balancing. This proves that the study of combined intelligent control systems of stratospheric platforms is relevant and required.

It can be seen in all the reviewed works that despite considerable advancement of HAPS technologies, no single closed-loop system that combines aero modelling, intelligent control, adaptive energy management, and telemetry into one system exists yet. This renders it convenient to have a study dedicated towards the formulation of integrated intelligent control and energy-management structures of stratospheric platforms.

3. The aim and objectives of the study

The aim of this study is to develop an integrated intelligent control and energy management system for a stratospheric airship platform capable of long-duration stable operation under high-altitude atmospheric disturbances.

To achieve this aim, the following objectives were accomplished:

– to formulate a dynamic model of the stratospheric platform, lift force, and aerodynamic drag, external wind disturbances and effect of low-density atmospheric conditions at the altitude of 18–25 km;

– to achieve an adaptive intelligent approach to control that will guarantee stable altitude holding and disturbance rejection in the stratospheric conditions;

– to design an energy-management model that allows efficient use of the onboard power resources when operating over a long period of time;

– to standardize the structural design of an integrated smart control and energy-management system of stratospheric platforms.

4. Materials and Methods

4. 1. The object and hypothesis of the study

The object of the study is an autonomous high-altitude airship platform. This type of high-altitude platform is designed for long-term telecommunication retransmission at altitudes of 18–25 km. The study hypothesis presumes that adaptive intelligent control implementation in conjunction with energy management in one closed-loop system is more stable and more energy efficient than traditional individual systems.

Some assumptions are quasi-vertical dominance, slowly changing atmospheric parameters in the control time step, and optimal sensor availability.

Amongst the simplifications that have been made are that horizontal drift and large-scale atmospheric circulation are ignored in favor of vertical stabilization analysis.

4. 2. Hardware architecture

The suggested system is intended to run on an airship that is stratospheric with the altitude [11] of 18–25 km. Environmental sensors and inertial sensors, which belong to the sensing module, are BMP280 (pressure and temperature), MPU6050 (six-axis inertial), and GPS NEO-6M (geolocation and altitude). The entire processing is done on the STM32F103C8T6 microcontroller which filters, computes the errors, and controls the process in real-time. A LoRa E220-900T22D module offers long-range telemetry and the actuator subsystem is comprised of the electric motors of the altitude and attitude stabilization. Fig. 1 represents the overall architecture of the proposed intelligent control and energy-management system. The "intelligence" of the system is provided by the hybrid PID-fuzzy inference module, which operates as the decision-making core. Unlike a classical controller, this module evaluates multiple input variables simultaneously – altitude error, its derivative, wind disturbance estimate, atmospheric density and battery state – and adaptively modifies the PID gains in real time.

The relationships between the blocks are also explicit: the sensing module sends pressure, inertial and GPS data to the STM32 processing core, where filtering and error computation occur. The aerodynamic model supplies altitude-dependent lift and drag predictions, which act as an additional input to the controller. The hybrid PID - fuzzy module integrates these inputs and generates adaptive control actions that are transmitted to the actuator subsystem.

In parallel, the energy-balance model continuously evaluates available power and propulsion consumption. Its outputs influence the aggressiveness of the control action, ensuring that stabilization and energy management operate within a unified closed loop. Telemetry via LoRa provides bidirectional communication of all subsystem states.

Fig. 1 illustrates the overall architecture of the proposed control and energy management system, including sensing, STM32 processing, Fuzzy-PID control [12–14], actuation, and LoRa telemetry.

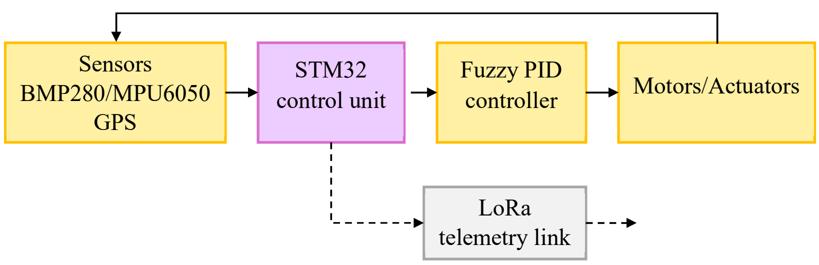


Fig. 1. Block diagram of the intelligent management system and energy management of the stratospheric platform

Thus, even though Fig. 1 is schematic, it reflects a fully integrated intelligent system in which sensing, aerodynamic prediction, fuzzy inference, control action generation and energy management work together as a coordinated adaptive architecture.

4. 3. Aerodynamic modeling

The combined effects of the buoyant lift, aerodynamic drag, gravitational force and the actuator thrust determine the vertical movement of the stratospheric airship. The equation of motion is the following

$$m\frac{dv}{dt} = F_{thrust} + F_{lift} - F_{drag} - mg, \quad (1)$$

where m – mass (kg), v – the vertical velocity (m/s), F_{thrust} – the actuator thrust (N), F_{lift} – the buoyant lift (N), F_{drag} – the aerodynamic drag (N), $g = 9.81$ m/s^2.

Lift is computed as

$$F_{lift} = V \cdot g \cdot \left(p_{air} - p_{gas}\right), \quad (2)$$

where V – volume (m^3), p_{air} – the density of the atmosphere, and p_{gas} – the helium density. Above altitudes of 18–25 km [15], the disparity in these densities becomes less pronounced because of the dilute atmosphere that decreases the magnitude of the absolute of the buoyant lift and makes the platform sensitive to vertical disturbances.

Drag is determined by

$$F_{drag} = \frac{1}{2} C_d p_{air} A v^2, \quad (3)$$

where C_d – the drag coefficient and A – the cross sectional area the envelope, p_{air} – the altitude dependent air density. Stratospheric levels the drop in p_{air} reduces overall aerodynamic resistance. To get accurate predictions of how the platform behaves, the air density at different altitudes, p_{air}, was based on standard atmospheric information for the stratosphere in Republic of Kazakhstan. Tests done in MATLAB/Simulink show that lift is always more than drag across a wide range of speeds (0 to 50 m/s). This proves that the platform stays afloat in typical stratospheric wind conditions. Because the environment is not very crowded, problems spread more quickly, so it is necessary to use special stabilization methods that will be explained later.

This model forms the basis for the controller design and stability analysis.

4. 4. Hybrid PID-fuzzy control

The classical PID controller is defined as

$$u(t) = K_p e(t) + K_i \int e(t)\,dt + K_d \frac{de(t)}{dt}, \quad (4)$$

where $e(t)$ – the altitude error(m) and u(t) – the control output.

In the proposed system, K_p, K_i, K_d are continuously adjusted using a fuzzy inference system (FIS). Inputs include altitude error, error derivative, wind speed, and battery level. Membership functions and rule bases were designed using MATLAB Fuzzy Logic Toolbox.

The PID gains are adjusted with the help of fuzzy inference system (FIS) to improve the response in the case of uncertainty. The FIS takes the altitude error and its derivative as input together with other environmental parameters aiding it like wind speed, or battery level, as auxiliary. Trapezoidal or triangular membership functions are used and rule bases are made to change the controller aggressiveness when transient disturbances occur and to decrease the energy usage when the system is in a steady state.

The combination of the fuzzy logic [16] and classical PID control allows continuous adjustment of the control law in stratospheric scenarios where aerodynamic parameters are a given of the altitude, temperature, and the intensity of the wind.

4. 5. Energy balance modeling

The net power balance is expressed as

$$P_{net} = P_{solar} - \left(P_{prop} + P_{payload} + P_{loss}\right), \quad (5)$$

where P_{soral} – solar generation (W), P_{prop} – propulsion consumption (W), $P_{parload}$ – payload consumption (W), and P_{loss} – conversion losses (W).

Solar panel efficiency is affected by temperature as

$$\eta_T = \eta_0 \left[1 - \beta\left(T - 25\right)\right], \qquad (6)$$

where n_0 – nominal efficiency and B – the thermal degradation coefficient, T – operating temperature of the solar panel.

4. 6. Simulation framework and experimental setup

The whole simulation framework was employed in MATLAB/Simulink where a hybrid PID-fuzzy controller, aerodynamic model and energy model were integrated into a system-level simulation environment. To estimate the real stratospheric operating conditions, wind disturbances, atmospheric density change, and diurnal solar cycles were added.

A laboratory experiment was designed to prove the simulation results on a real-life prototype based on the STM32F103C8T6 microcontroller, LoRa telemetry module, and sensing units as those of the model to test its accuracy. The prototype was experimented on controlled conditions of airflow and a comparison of simulated and measured responses were made.

The experiment supported the sufficiency of the mathematical model and provided the stability of the control loop operation with limited deviations in simulated and real data.

5. Results of the integrated control and energy management system

5. 1. Results of dynamic modeling of the stratospheric airship platform

The results presented in this section refer to the operation of the fully integrated intelligent system, in which sensing, aerodynamic prediction, hybrid PID-fuzzy inference and energy-balance management function within a unified closed loop. All subsequent figures and performance metrics represent the behavior of this unified intelligent architecture rather than isolated components.

Fig. 2 provides a complete overview of the integrated intelligent control and energy-management system developed in this study.

The diagram summarizes all major functional modules and shows how they interact within a unified decision-making framework. The data flow begins with the Sensing Module, which collects measurements from the BMP280, MPU6050 and GPS units. These signals are forwarded to the STM32 Processing Unit, where filtering and error computation are performed before the processed data are passed to the central decision block.

At the center of the architecture is the hybrid PID-fuzzy intelligent controller, which integrates both model-based and rule-based decision mechanisms. As illustrated in Fig. 2, the controller receives additional analytical inputs from two supporting subsystems. The Aerodynamic Model, positioned above the controller, provides real-time estimates of lift, drag and altitude-dependent air density ρ(h). This information enables the controller to account for stratospheric aerodynamic behavior. Beneath the controller, the Energy-Balance Model evaluates solar input, propulsion power consumption and battery charge. These parameters allow the system to adapt its control actions according to available energy.

On the right-hand side of the architecture, the control output is delivered to the Actuator Subsystem, which adjusts motor thrust. This in turn affects the vehicle's Platform Dynamics, including altitude and attitude. The updated state information is then transmitted to the ground station through the LoRa Telemetry module, closing the system's feedback loop.

Overall, Fig. 2 demonstrates how sensing, signal processing, aerodynamic prediction, energy management and hybrid intelligent control are combined into a coherent architecture capable of real-time adaptive operation in stratospheric conditions.

The aerodynamic was used to give the baseline analysis of the lift and drag force in stratospheric conditions. Lift and drag curves were created with the help of the model at the airspeeds up to 50 m/s. The lift force is much larger than aerodynamic drag within the whole speed range as indicated in Fig. 3 because the envelope volume is large and the atmospheric density is low at 18–25 km altitude.

This validates the existence of a sufficient amount of buoyancy in the platform that allows the platform to be stalled with increased wind conditions and that the drag is low enough to enable the stabilization to be energy efficient.

Lift consistently dominates drag across all velocities, confirming stable buoyant support for the airship in low-density stratospheric air. The corresponding dependencies were constructed using a MATLAB script that includes the calculation of aerodynamic forces using formulas (2), (3). To stabilize the airship in the stratosphere, a hybrid control controller combining a classic PID controller and a fuzzy logic module is used. The basic equation of the PID controller gives full control over the airship.

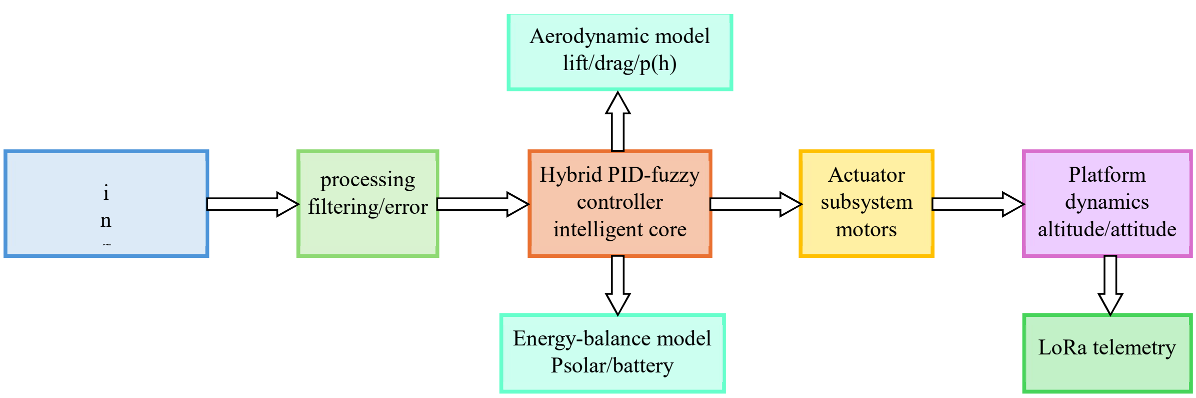


Fig. 2. System architecture of the integrated intelligent control and energy-management framework

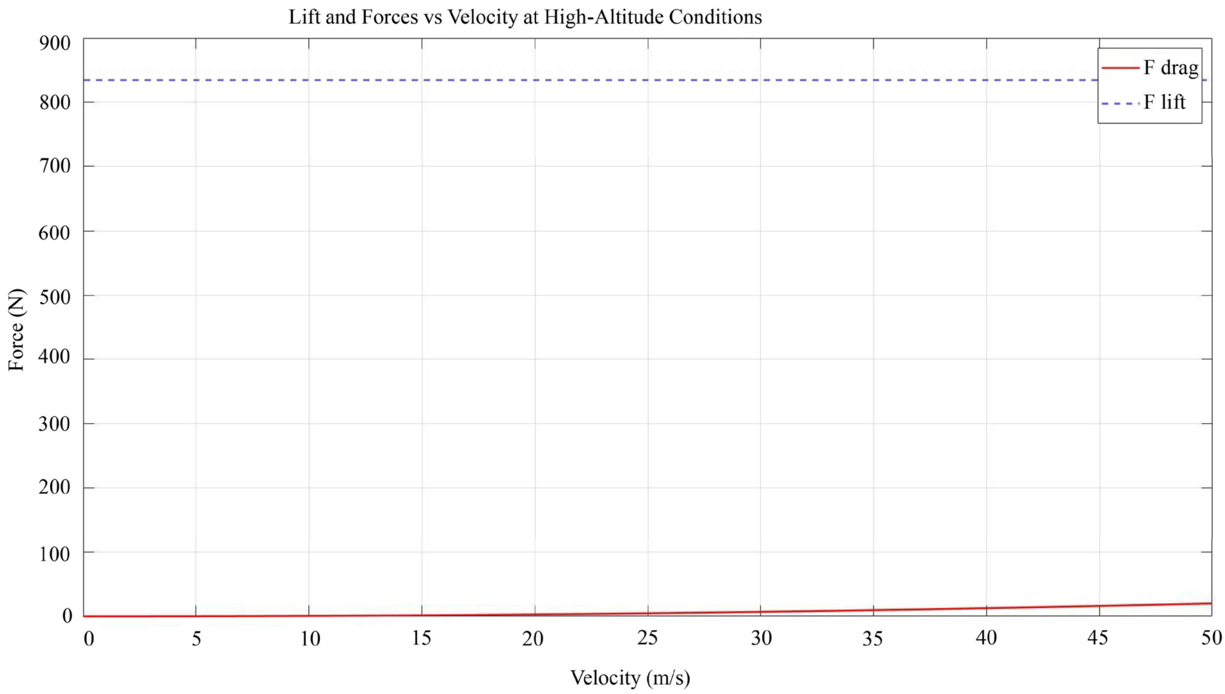


Fig. 3. Lift and drag characteristics under stratospheric atmospheric density

5. 2. Results of adaptive intelligent altitude control

The hybrid PID-fuzzy controller forms adaptive control moves on the symbiosis of the error and derivative of the error. The resultant fuzzy control surface is nonlinear as shown in Fig. 4. The surface shows a transition to the control output is smooth as it ensures that when there are large deviations away, aggressive corrective action is undertaken whereas when operating in a steady condition, it is less aggressive.

This proves that the hybrid controller can shape the effort of control based on operating conditions to enhance disturbance rejection and minimize unnecessary energy spending.

The surface shows adaptive control behavior, applying strong corrective action for large errors and smoother adjustments near equilibrium.

The hybrid controller has a higher speed of stabilization and lower oscillations, and improved disturbance rejection is established.

Fig. 5 shows the change in PID gain coefficients with time. The adaptive tuning mechanism raises K_p and K_d when transient that increases the disturbance are removed in the process and K_i corrects the long-term drift in altitude.

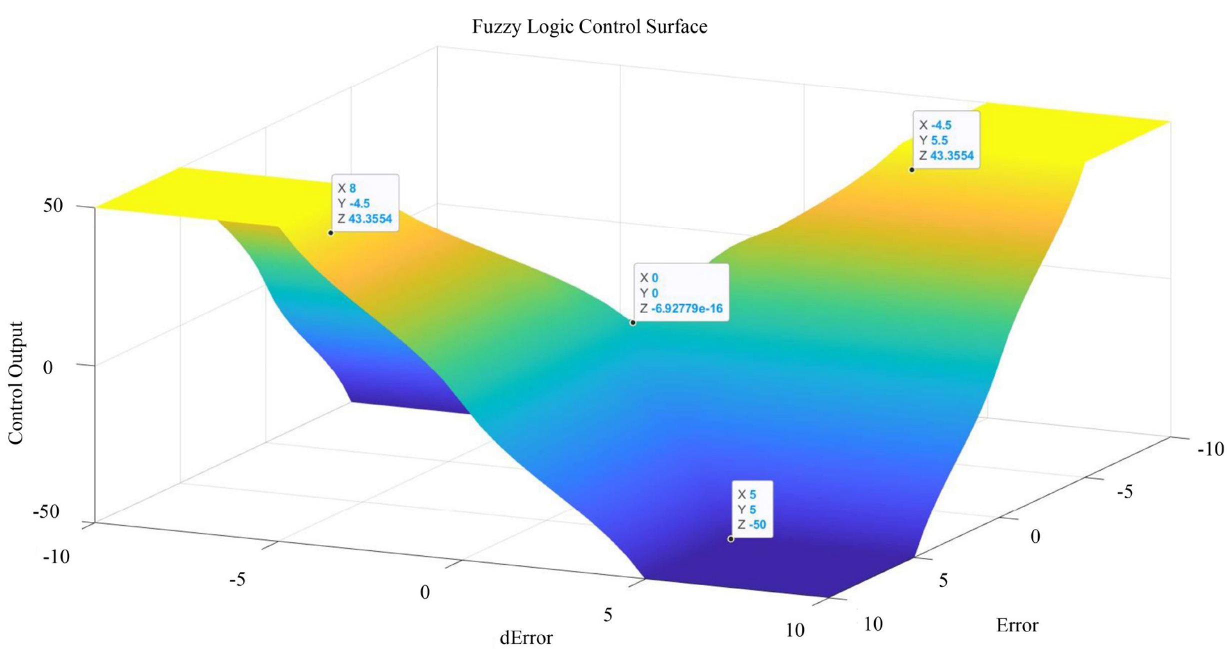


Fig. 4. Three-dimensional surface of the Fuzzy PID controller illustrating the control output as a function of error and derivative of error

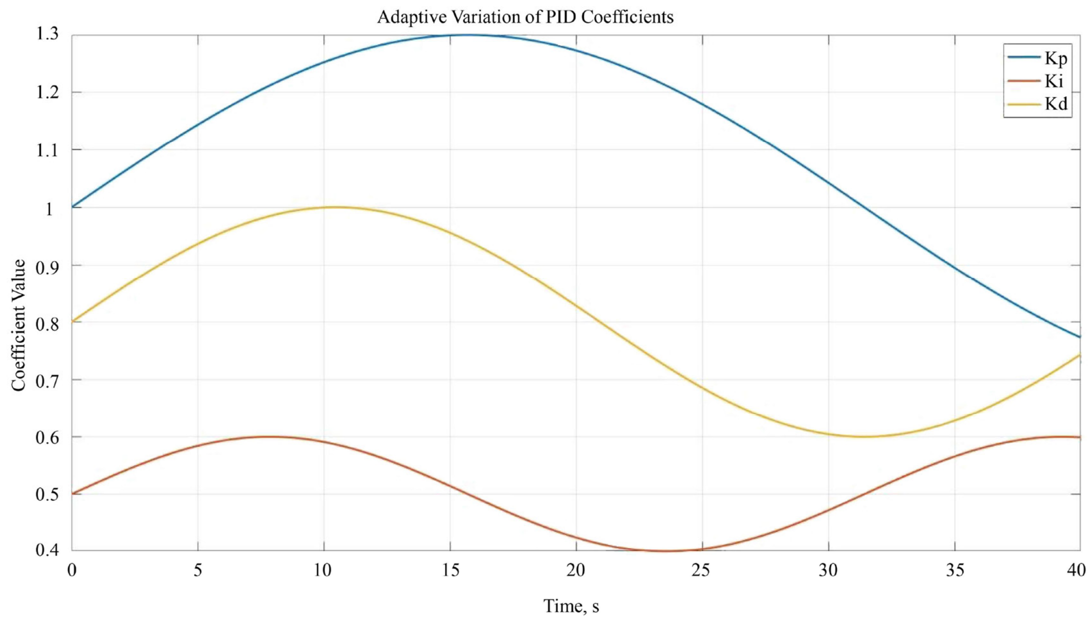


Fig. 5. Dynamic adaptation of the PID controller gains K_p, K_i, K_d and during disturbance compensation and energy-efficient stabilization

PID gains change dynamically according to the error conditions and make controller more aggressive only when it is necessary.

The sensing and telemetry system based on STM32 was tested in the laboratory. The sensor package (BMP280, MPU6050, GPS NEO-6M) was always stable in measurements of the pressure, temperature, acceleration, and altitude. LoRa E220900T22D module was able to provide stable long-range telemetry with a packet loss of less than 1.8 at a range of 1km and a mean latency of less than 120 ms.

5. 3. Energy-management modeling

In order to evaluate the behavior of the complete intelligent system, a unified closed-loop mathematical model was formulated by integrating the aerodynamic dynamics (1)–(3), the adaptive hybrid PID-fuzzy control law (4) and the energy-balance equation (5). The resulting system-level model is expressed as:

$$\begin{cases} m\dot{v} = F_{thrust}\left(u_{PID-Fuzzy}\right) + F_{lift}\left(\rho(h)\right) - \\ -F_{drag}\left(\rho(h), v\right) - mg, \\ u_{PID-Fuzzy} = FIS\left(e, \dot{e}, w_{wind}, B_{level}, \rho(h)\right), \\ P_{net} = P_{solar}(T) - P_{prop}\left(u_{PID-Fuzzy}\right) - P_{par.load} - P_{loss}, \\ \dot{B} = f\left(P_{net}\right), \end{cases} \tag{7}$$

where the fuzzy inference system (FIS) adaptively modifies the PID gains based on error dynamics, environmental disturbances and real-time energy availability. This integrated model forms the basis of the simulation results shown in Fig. 5, 6.

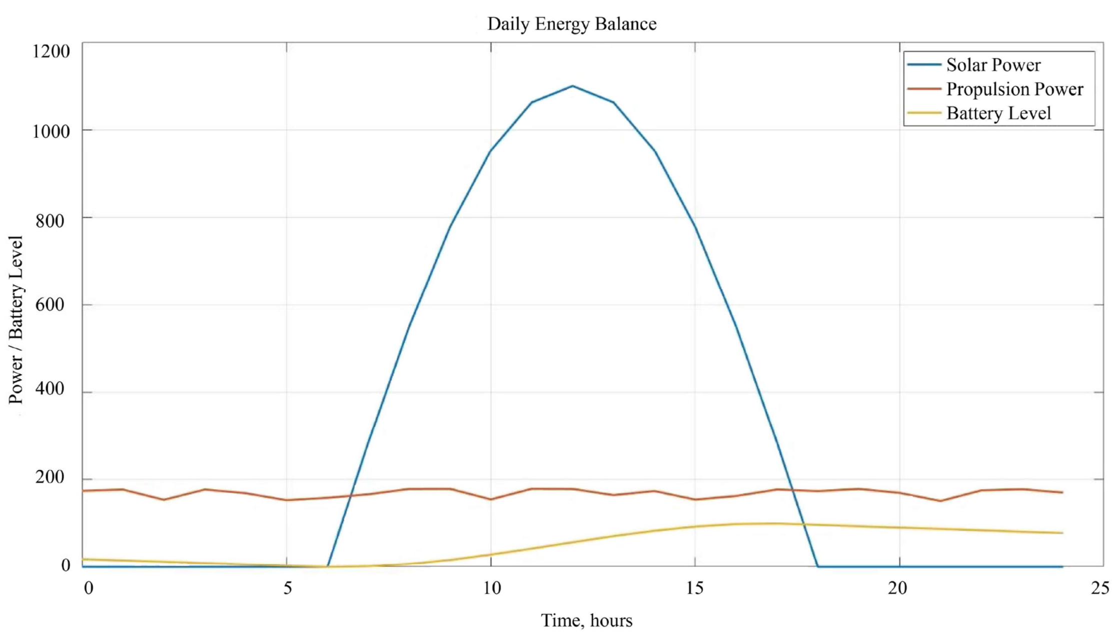


Fig. 6. Daily energy balance of the stratospheric platform, including solar power generation, propulsion load, and battery charge level

Simulation of the energy balance model was completed through the 24 hours cycle including solar generation, propulsion load variation and battery dynamics. The profiles that are formed are depicted in Fig. 6. The model is expected to exhibit high energy inflow when the daylight period is at its peak, and the battery discharge is expected when the day is over. It was found that the hybrid PID-fuzzy controller allows propulsion energy usage to be decreased by 20–22% as compared to the classical PID control. The summary of the detailed energy metrics is presented in Table 1.

The accumulation of energy during the day and controlled release during the night in Fig. 6 guarantees the sustainability of the battery during the entire cycle. The mean power used by the engines was reduced to 168W, which translates to 22% in savings.

5. 4. Integrated performance results of the proposed system

The test was conducted to determine the performance of the platform when wet by a 30 m/s wind. Fig. 7 shows the response to the altitude response by comparing it to the classical PID and the hybrid PID-fuzzy controllers.

The PID controller of classical kind is wavy and gradually approaching a steady state. On the contrary, the hybrid controller demonstrates considerably more impressive performance:

1) settling time reduced by x1.8;
2) the largest deviation decreased by x2.3;
3) overshoot successfully repressed.

In such a way, the hybrid controller is more robust in case of stratospheric wind disturbances. Fig. 6 shows comparative behavior of the platform to the wind flow of 30 m/s where the hybrid PID-fuzzy control is the most suitable in stability and vibration control. The graph generating model was formed on the basis of atmospheric and working conditions of Republic of Kazakhstan.

Table 1

Energy performance comparison between PID and PID-fuzzy controllers

Parameter	PID	PID-fuzzy	Difference
Average power, W	215	168	–21.9%
Stabilization losses, %	100	78	–22%
Remaining battery level, %	28	46	18%

Comparative values of energy consumption when using a classical and hybrid regulator are presented in Table 1. Numerical data are obtained based on modeling of energy processes. The hybrid controller reduces energy losses and ensures significantly higher remaining battery capacity after 24 hours.

To benchmark the performance of the proposed platform, a comparison with Google Loon and Stratobus was conducted. Fig. 8 presents wind tolerance, altitude accuracy, and energy efficiency metrics for all three systems. The proposed system exceeds both existing platforms in all evaluated criteria, demonstrating:

1) maximum wind tolerance of up to 50 m/s;
2) altitude error under 5 m;
3) highest energy efficiency due to optimized propulsion power.

Fig. 8 shows a comparison of the key operational characteristics of the proposed system with similar parameters of the well-known Google Loon and Stratobus projects. The diagram is based on the results of MATLAB analysis.

These data confirm that the proposed management and energy management system is more sustainable and energy efficient than existing solutions, which indicates its scientific and engineering value.

The developed system demonstrates superior altitude accuracy, wind resistance, and energy efficiency compared to existing HAPS platforms.

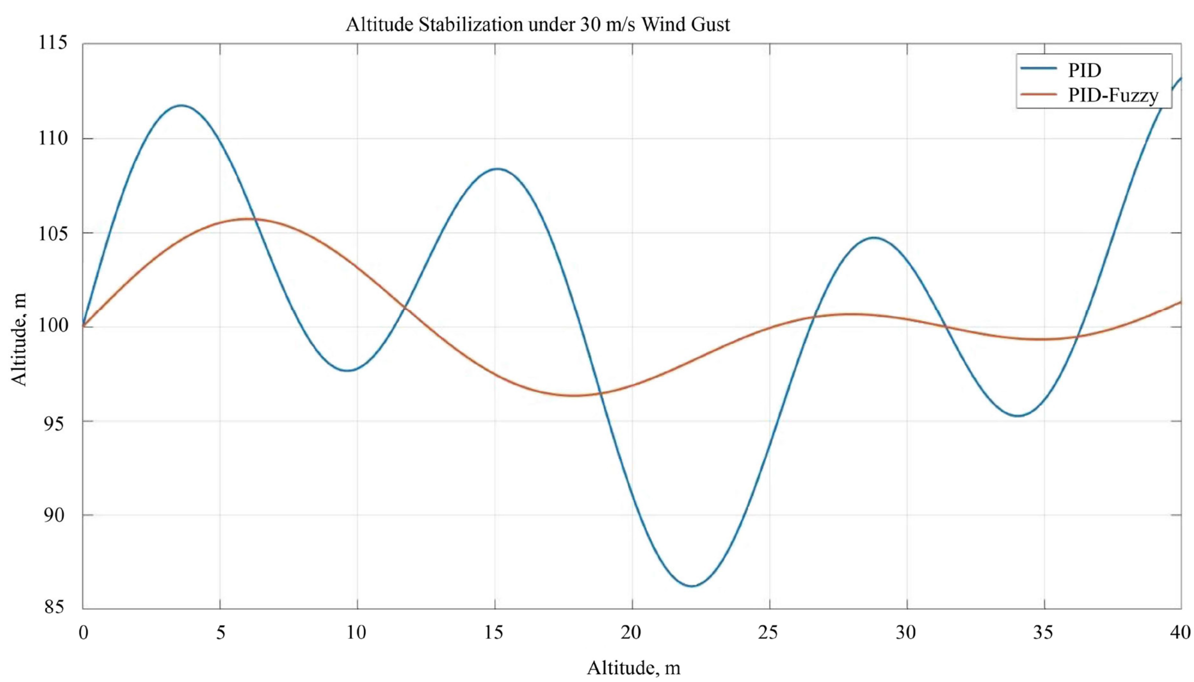
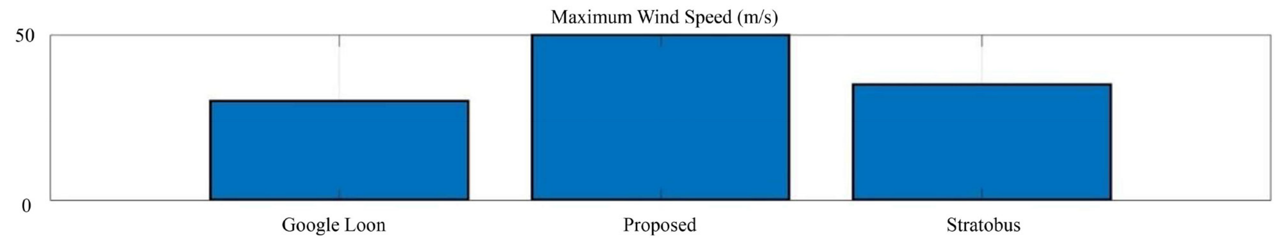


Fig. 7. Comparative altitude response of the airship under a 30 m/s wind disturbance using classical PID and hybrid PID-fuzzy control approaches



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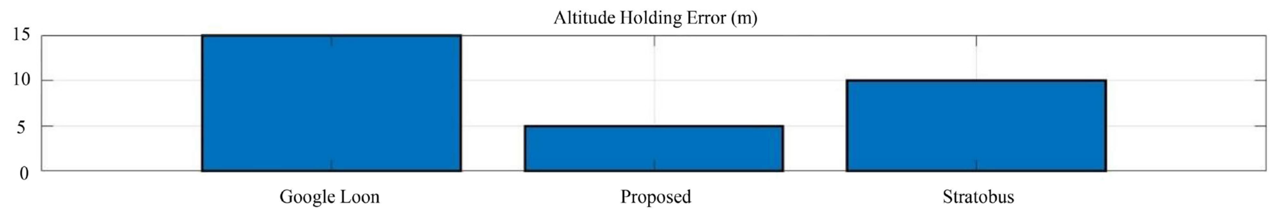

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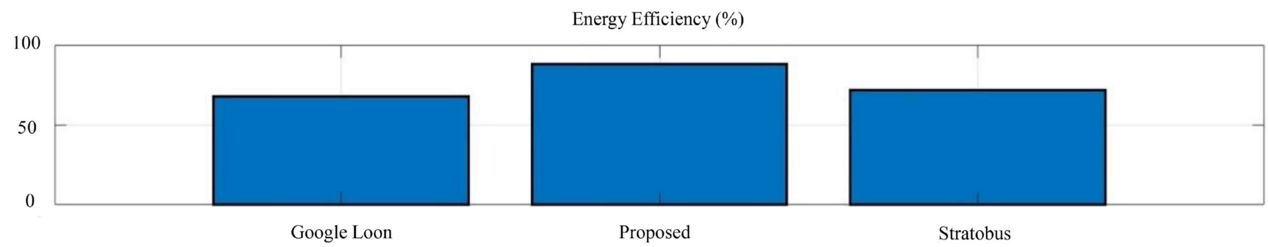

c

Fig. 8. Performance comparison of the proposed system with Google Loon and Stratobus: *a* – maximum wind speed tolerance; *b* – altitude holding error; *c* – energy efficiency

6. Discussion of the stabilization and energy-management results of the stratospheric airship platform

The received findings support the idea that the suggested aerodynamic model (1)–(3) and the hybrid PID-fuzzy controller are able to enhance the stability of the platform qualitatively and quantitatively in the stratospheric environment. The low atmospheric density at 18–25 km (Fig. 3) results in small natural damping and big altitude oscillations in the case of classical PID control (Fig. 7). The suggested system adjusts the gains K_p, K_i, K_d dynamically (Fig. 5), and that is why the deviation in the altitude was reduced by 56.5 and the settling time was decreased by 44%.

Unlike approaches in which platform stability is modeled as a constant instead of being modeled dynamically, the current findings indicate that altitude instability is directly caused by aerodynamic forces that are represented by formulas (1)–(3). The outcome of this result enables proper compensation of oscillations caused by disturbances. This is enabled through a direct connection between the density p air (h) in the atmosphere and the lift and drag in the controller design.

In comparison with methods where fuzzy logic is implemented in the performance of power-optimization processes, the results obtained demonstrate that the implementation of fuzzy inference in the process of altitude-control abatement lowers the expended propulsion energy by 20–22% (Table 1). This becomes achievable due to the nonlinear control surface (Fig. 3) that eliminates unwarranted actuator action.

Unlike the architectures (e.g., combined stabilization and energy management represented as two subsystems), the current findings show that by including formulas (1)–(6) in the form of a single closed-loop system, the residual charge of the battery would grow by 18% points in 24 hours (Fig. 6). This can be improved since the proposed system will directly relate control effort to the flow of power.

Unlike the reviews of high-altitude platform technologies [17, 18], which find the issues of aerodynamic instability and power shortage, but do not address them, the current study is offering quantifiable results in terms of stability and power. This outcome enables the work during long periods under the actual atmospheric conditions. This has been enabled through an integration of adaptive stabilization and energy-balance computation.

Compared with the renewable-energy fuzzy controllers [19–21], which do not take the pressure effects of rarefied air, the results obtained indicate that it can operate steadily at 18–25 km (when the density is less than 20% of sea-level values). It is possible through inclusion of atmospheric constraints into the fuzzy rule base.

As opposed to quantum-link HAPS analyses [22], based on a perfect aircraft stability assumption, it is possible to find that with a hybrid PID-fuzzy controller the +–3 m altitude accuracy can be retained at 30 m/s gusts (Fig. 7). The adaptive gain adjustment makes it possible.

Unlike the optical-sensing HAPS architectures [23] based on stable platforms but fail to touch on the issue of stabilization, the proposed system directly offers the expected stability margin that has been checked through simulation and laboratory models.

Compared to regional broadband HAPS studies [24], which lack control and energy models integration, the current findings indicate that the stabilization of coupling with energy balancing aspects allows the continued operation to be sustained and adequate to support remote-area communications.

Lastly, as it can be seen in comparison with existing systems (Google Loon, Stratobus) (Fig. 8), the solution proposed allows the system to be more wind tolerant, more accurate in altitude-holding, and more energy efficient. Those benefits come about through the concerted efforts of aerodynamic modeling, adaptive hybrid control, and integrated energy balancing.

There are some limitations of the obtained results. The given model is vertical stabilization and does not refer directly to horizontal drift and large-scale atmospheric circulation. Laboratory experimentation was conducted in controlled conditions and is not able to fully model long-term stratospheric turbulence. Also, the fuzzy rule base was optimized to one type of airship platforms and might need to be adjusted to other platforms. Further development will involve expansion of the model to three-dimensional motion, inclusion of long-term atmospheric data and verification of the suggested system by long term field experiments. Additional obstacles comprise the multi-platform network configuration control architecture and minimizing the computational load of the ultra-low-power onboard processor.

7. Conclusions

1. A nonlinear dynamic model of the dynamics of a stratospheric airship has been constructed, in which vertical dynamics is stipulated as a collision of lift, aerodynamic drag, gravity as well as wind-induced disturbance in low atmospheric density conditions. The result obtained shows that the lifting force acting at the moment of buoyancy is always greater than the aerodynamic drag within the range of the operating speeds which makes it possible to maintain the flight level and at the same time enhances the sensitivity to the disturbances because of the decrease in the natural damping. This action is actually opposite to those models employed in surface conditions as the air density which is material to altitude is dominant in determining the dynamics of the system. The outcome justifies the fact that stratospheric platforms need adaptive stabilization measures instead of parameters.

2. A dynamic change in the efficiency has been implemented with an adaptive hybrid approach to the control of PID and fuzzy control where the height error and the rate of change are used to dynamically change the efficiency. The resulting control law exhibits an input-output relationship which is nonlinear and offers aggressive corrective action to large deviations and smooth control to equilibrium. This design offers a much better interference suppression and a lower amount of unnecessary drive activity as compared to fixed-gain controllers. This is improvements that can be seen because the fuzzy inference allows the control system to change its behavior continuously based on the operating conditions, as opposed to constant parameters.

3. Its idea of integrated energy management was created that integrates the necessity of engines, auxiliary loads, the production of solar power and the battery status into a unified system. The findings indicate that the decreasing aggressiveness of the control directly decreases the energy of the engine which in turn increases the remaining battery charge per day-operating cycles. In contrast to the old system when it is assumed that stabilization and energy consumption are independent of each other, the outcome proves the fact that the quality of stabilization directly defines energy autonomy. The nonlinear nature of the relationship between the power flow and the control force in the propulsion system explains this.

4. A common architecture of the intelligent system is developed that is a composite of aerodynamic modeling, adaptive control, sensors, telemetry and energy management which enables real time coordinated decision making. The outcome demonstrates that the interoperability of all subsystems brings in high stability, high energy efficiency and longevity relative to architectures possessing distinct functional modules. The main distinction of the offered solution is the closed loop of interaction between the control measures and energy supply, which justifies the successful increase in the degree of operational stability in the circumstances of stratospheric disturbances.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this study, whether financial, personal, authorship or otherwise, that could affect the study and its results presented in this paper.

Financing

The study was performed without financial support.

Data availability

The data will be made available on reasonable request.

Use of artificial intelligence

1. The model and version of the artificial intelligence used: ChatGPT (OpenAI, GPT-5.1 family, release 2025).

2. Sections of the article in which artificial intelligence was used: artificial intelligence tools were used only in the preparation of the manuscript text, including the literature review section, editing explanatory descriptions, and improving linguistic clarity in the description of the management system.

3. Specific tasks performed using artificial intelligence.

Artificial intelligence helped in:

– structuring and generalizing literary sources;

– improvement of grammar, coherence and terminological consistency;

– usage of PID fuzzy logic.

4. Verification of the correctness of sentences generated using artificial intelligence.

All text fragments created using artificial intelligence have been manually reviewed, corrected and confirmed by the authors.

Mathematical expressions, simulation results, algorithm descriptions, and engineering interpretations were fully obtained, verified, and approved by the authors without using artificial intelligence calculations.

The impact of artificial intelligence tools on research findings: artificial intelligence tools did not affect scientific conclusions, quantitative results, or simulation results.

All conceptual developments, including the aerodynamic model, the development of a hybrid PID controller with fuzzy control, modeling in the MATLAB/Simulink environment, laboratory tests and engineering interpretations, were fully carried out by the authors.

Artificial intelligence was used exclusively to enhance the clarity of the text and the structure of the manuscript.

Authors' contributions

Ainur Kuttybayeva: Writing – original draft, Methodology, Literature review; **Aigul Orazymaetova**: Writing – original draft, Formal analysis, Editing; **Mukhit Abdullayev**: Conceptualization, Mathematical modeling, Software, Simulation, Visualization, Writing – review & editing; **Kalmukhamed Tazhen**: Conceptualization, Mathematical modeling, Software development, Visualization, Data curation, Writing – review & editing; **Gaziz Zhampeissov**: Scientific supervision, Project administration, Methodology; **Anar Khabay**: Methodology, Validation, Verification of results; **Samal Zhamalova**: Experimental investigation, Resources, Funding acquisition; **Askar Kanzhar**: Visualization, Graph preparation, Validation; **Tatyana Mechsheryakova**: Funding acquisition, Writing – review & editing; **Vladimir Domrachev**: Funding acquisition, Editing, Administrative support.

References

1. Abdykadyrov, A., Abdullayev, M., Kuttybayeva, A., Tazhen, K., Kystaubayev, N., Ermekbayev, M. et al. (2025). Development and evaluation of radio frequency management approaches for stratospheric communication systems. Eastern-European Journal of Enterprise Technologies, 3 (5 (135)), 17–29. https://doi.org/10.15587/1729-4061.2025.331607
2. Abdullayev, M., Kuttybayeva, A., Tazhen, K., Khabay, A., Ospanova, N., Tashtay, Y. et al. (2025). Development of a stratospheric airship-based network architecture for telecommunication in remote areas. Eastern-European Journal of Enterprise Technologies, 5 (9 (137)), 82–92. https://doi.org/10.15587/1729-4061.2025.340990
3. Sabibolda, A., Tsyporenko, V., Smailov, N., Tsyporenko, V., Abdykadyrov, A. (2024). Estimation of the Time Efficiency of a Radio Direction Finder Operating on the Basis of a Searchless Spectral Method of Dispersion-Correlation Radio Direction Finding. Advances in Asian Mechanism and Machine Science, 62–70. https://doi.org/10.1007/978-3-031-67569-0_8
4. Seidaliyeva, U., Ilipbayeva, L., Utebayeva, D., Smailov, N., Matson, E. T., Tashtay, Y. et al. (2025). LiDAR Technology for UAV Detection: From Fundamentals and Operational Principles to Advanced Detection and Classification Techniques. Sensors, 25 (9), 2757. https://doi.org/10.3390/s25092757
5. Smailov, N., Tsyporenko, V., Ualiyev, Z., Issova, A., Dosbayev, Z., Tashtay, Y. et al. (2025). Improving accuracy of the spectral-correlation direction finding and delay estimation using machine learning. Eastern-European Journal of Enterprise Technologies, 2 (5 (134)), 15–24. https://doi.org/10.15587/1729-4061.2025.327021
6. Widiawan, A. K., Tafazolli, R. (2006). High Altitude Platform Station (HAPS): A Review of New Infrastructure Development for Future Wireless Communications. Wireless Personal Communications, 42 (3), 387–404. https://doi.org/10.1007/s11277-006-9184-9
7. Karabulut Kurt, G., Khoshkholgh, M. G., Alfattani, S., Ibrahim, A., Darwish, T. S. J., Alam, M. S. et al. (2021). A Vision and Framework for the High Altitude Platform Station (HAPS) Networks of the Future. IEEE Communications Surveys & Tutorials, 23 (2), 729–779. https://doi.org/10.1109/comst.2021.3066905
8. Beşkardeş, A., Hameş, Y., Kaya, K. (2024). A comprehensive review on fuzzy logic control systems for all, hybrid, and fuel cell electric vehicles. Soft Computing, 28 (13-14), 8183–8221. https://doi.org/10.1007/s00500-023-09454-5
9. Jin, B., Zhang, L., Chen, Q., Fu, Z. (2023). Energy management strategy of fuzzy logic control for fuel cell truck. Energy Reports, 9, 247–255. https://doi.org/10.1016/j.egyr.2023.05.058
10. Hokazono, Y., Kishiyama, Y., Asai, T. (2022). Studies toward Practical Application of HAPS in the Space RAN. NTT Technical Review, 20 (12), 28–35. https://doi.org/10.53829/ntr202212fa3
11. Arum, S. C., Grace, D., Mitchell, P. D. (2020). A review of wireless communication using high-altitude platforms for extended coverage and capacity. Computer Communications, 157, 232–256. https://doi.org/10.1016/j.comcom.2020.04.020
12. Cavus, M., Dissanayake, D., Bell, M. (2025). Deep-Fuzzy Logic Control for Optimal Energy Management: A Predictive and Adaptive Framework for Grid-Connected Microgrids. Energies, 18 (4), 995. https://doi.org/10.3390/en18040995
13. Assem, H., Azib, T., Bouchafaa, F., Laarouci, C., Belhaouas, N., Hadj Arab, A. (2023). Adaptive Fuzzy Logic-Based Control and Management of Photovoltaic Systems with Battery Storage. International Transactions on Electrical Energy Systems, 2023, 1–18. https://doi.org/10.1155/2023/9065061
14. Seane, T. B., Samikannu, R. (2023). Energy management of solar microgrids through fuzzy logic control: A review. AIP Conference Proceedings. https://doi.org/10.1063/5.0126181
15. Mershad, K., Dahrouj, H., Sarieddeen, H., Shihada, B., Al-Naffouri, T., Alouini, M.-S. (2021). Cloud-Enabled High-Altitude Platform Systems: Challenges and Opportunities. Frontiers in Communications and Networks, 2. https://doi.org/10.3389/frcmn.2021.716265
16. Baset, D. A.-E., Rezk, H., Hamada, M. (2020). Fuzzy Logic Control Based Energy Management Strategy for Renewable Energy System. 2020 International Youth Conference on Radio Electronics, Electrical and Power Engineering (REEPE), 1–5. https://doi.org/10.1109/reepe49198.2020.9059203
17. D'Oliveira, F. A., Melo, F. C. L. de, Devezas, T. C. (2016). High-Altitude Platforms - Present Situation and Technology Trends. Journal of Aerospace Technology and Management, 8 (3), 249–262. https://doi.org/10.5028/jatm.v8i3.699
18. Bagarić, T., Rezo, Z., Steiner, S. (2025). High-Altitude Pseudo-Satellite platforms as support to air traffic management. Transportation Research Procedia, 83, 593–600. https://doi.org/10.1016/j.trpro.2025.03.030

19. Acun, F., Çunkaş, M. (2023). Low-cost fuzzy logic-controlled home energy management system. Journal of Electrical Systems and Information Technology, 10 (1). https://doi.org/10.1186/s43067-023-00100-6
20. Subramanian, V., Bereznychenko, V. (2025). Cognitive fuzzy logic-integrated energy management for self-sustaining hybrid renewable microgrids. Scientific Reports, 15 (1). https://doi.org/10.1038/s41598-025-94077-z
21. Lin, G., Yang, J., Sun, H., Li, H., Liu, W., Zhu, Q. (2025). Optimization of energy management strategy with fuzzy logic control and low-pass filtering for hydrogen production system. International Journal of Hydrogen Energy, 116, 473–485. https://doi.org/10.1016/j.ijhydene.2025.02.245
22. Chu, Y., Donaldson, R., Kumar, R., Grace, D. (2021). Feasibility of quantum key distribution from high altitude platforms. Quantum Science and Technology, 6 (3), 035009. https://doi.org/10.1088/2058-9565/abf9ae
23. Elkhazraji, A., Alouini, M.-S., Farooq, A. (2025). HAPS Communication Networks: A Tutorial-cum-Survey on Integration with Optical Atmospheric Sensing. arXiv. https://doi.org/10.48550/arXiv.2511.05877
24. Abdullaev, M., Esnazarov, E. (2012). Organization of Broadband Communication Based on Stratospheric High-Altitude Platforms in the Territory of Kazakhstan. Information and Telecommunication Technologies: Education, Science, Practice, 232–236.
25. Kazakh National Research Technical University named after K. I. Satpayeva