

Design of electric heavy truck battery swapping UAV system under the background of low-altitude economy

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ABSTRACT

With the acceleration of the transformation of the global transportation energy structure, electric heavy-duty trucks are gradually becoming an important choice for future trunk logistics due to their clean and efficient characteristics. However, under the current situation that battery technology and infrastructure construction have not been fully matched, heavy trucks still face obvious endurance problems in long-distance transportation. At the same time, the rise of low-altitude economy provides new possibilities for cross-regional energy transmission and rapid energy replenishment. Based on this background, this paper attempts to explore a new energy replenishment method combined with air-ground coordination from the perspective of product design, namely the mobile flight battery replenishment system. The system takes the standardized and replaceable flight battery as the core, realizes the battery transportation and replenishment through medium and large UAVs, and combines the mobile base station pulled by electric heavy trucks to complete the dynamic energy delivery during driving. This paper analyzes the system composition, the appearance design of the core module, the interaction mode and the use process, aiming to provide a feasible design solution for solving the bottleneck problem of energy replenishment in the long-distance transportation of electric heavy trucks. The research results show that the solution has the advantages of flexible deployment, rapid response and efficient energy management, and has high application potential and industry prospects.

Keywords: Low-altitude economy; electric heavy-duty trucks; mobile flight batteries; UAV energy replenishment system.

INTRODUCTION

Background

At present, under the background of the continuous promotion of the "dual carbon" strategy and the adjustment of the global energy structure, the new energy vehicle industry is ushering in a wave of rapid growth. As an important force in road logistics to undertake heavy-duty and long-distance transportation tasks, the electrification trend of electric heavy-duty trucks is also becoming more and more clear. The promotion of such vehicles is regarded as one of the key levers to achieve low-carbon trunk transportation. However, due to the high energy consumption and high operation intensity of heavy trucks, they also face many challenges in the way of energy replenishment. (Agyekum *et al.*, 2023)

Whether it is relying on fixed fast charging piles or battery swap stations, there are many practical obstacles to the energy replenishment of electric heavy trucks. The electrification of heavy trucks is an important part of the development of new energy vehicles and a necessary measure to achieve a green transformation and development path. Compared with the charging mode, the battery swap mode can solve the problems of high purchase cost and long charging time of electric heavy trucks, effectively shorten the power supply time, and improve the transportation efficiency of heavy trucks. However, the construction cost of heavy truck battery swap station is high, and it is difficult for enterprises to build heavy truck battery swap stations on a large scale under the condition of limited funds, and the number of battery swap stations cannot meet the battery swap demand of heavy trucks, resulting in a decrease in market demand for battery swapping heavy trucks, which is not conducive to the development of heavy truck battery swapping mode. Therefore, the government needs to give it certain policy subsidies to encourage more enterprises to join the battery swap track. (Manzini, Martínez García & Harrivaara, 2025)

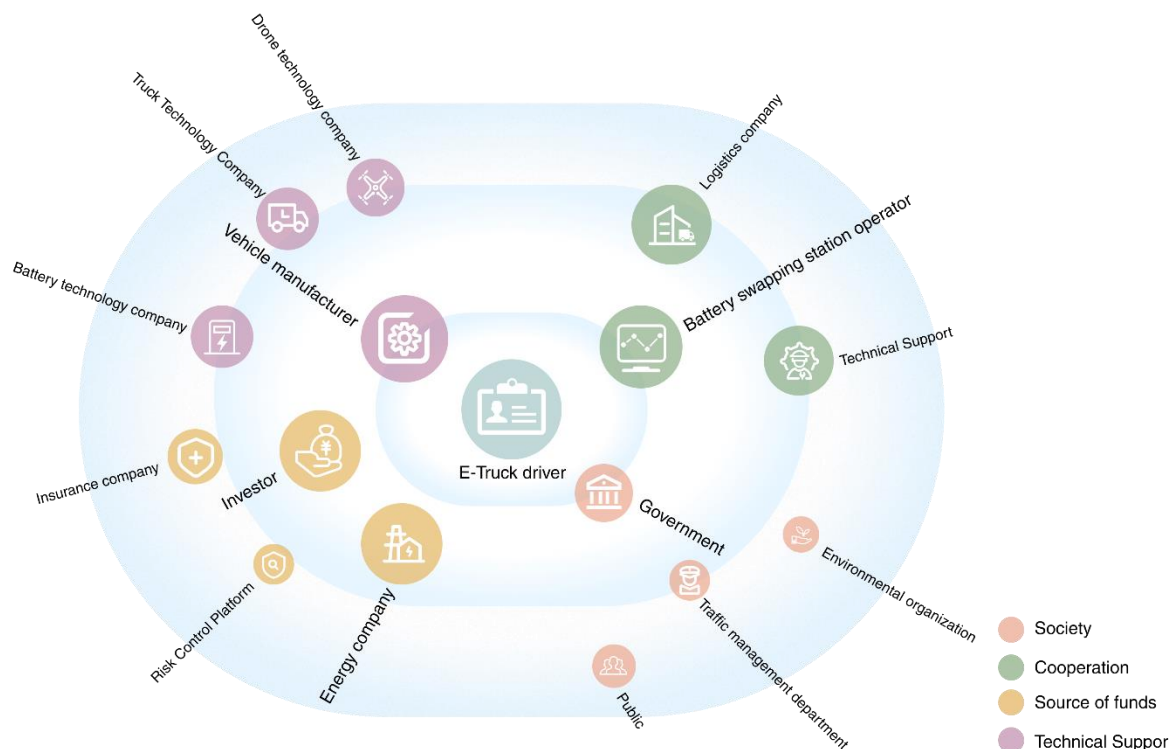
This trend provides an unprecedented possibility for breaking through the limitations of traditional energy replenishment methods. The "low-altitude economy" is at the heart of the discussion and is gradually gaining wider social awareness, highlighting the

high level of public concern and positive attitude towards it. This focus not only focuses on the growth potential, technological advances and policy environment that low-altitude economies bring, but also reflects public expectations that they will drive economic development, suggesting that low-altitude economies are seen as emerging engines of economic growth. The public's optimistic expectations for the low-altitude economic prospects have laid a good foundation for social cognition for its future development.

SYSTEM REQUIREMENTS ANALYSIS AND DESIGN CONCEPT

Application Scenario Assumption

With the inclusion of "low-altitude economy" as a national strategic emerging industry, its application in the field of air logistics and intelligent transportation is rapidly expanding. From UAV delivery to air-ground collaborative operation, a number of low-altitude scenarios have gradually matured, which has also brought practical feasibility to the deep integration of power systems and aerial platforms. In this context, considering the range limitation and energy replenishment dilemma faced by electric heavy-duty trucks in long-distance transportation, this paper proposes a "flight battery replenishment system" that integrates the concepts of low-altitude flight, battery standardization and intelligent scheduling (Figure 1).



Source: Self-painted.

Figure 1: Stakeholder map.

The core idea of the system is to provide dynamic power replenishment to the electric heavy truck while it is on the move, using a battery module on the drone platform. Its key support unit is a "mobile base station" modified from the front of an electric truck, which is equipped with four sets of standardized flight battery compartments, with battery charging, operation monitoring and autonomous deployment functions. The flight battery module has built-in flight control, battery management, electromagnetic locking and other subsystems, which can take off and land vertically, fly short distances, and complete energy replenishment operations with the target truck through standard electromechanical interfaces. (Arif *et al.*, 2021)

Typical application scenarios for the system include:

1. Operation route: It is mainly deployed in high-speed trunk lines (such as Beijing-Shanghai, Beijing-Hong Kong-Macao and other high-speed sections), covering hundreds of kilometers of heavy-duty transportation tasks.
2. Service objects: for bulk logistics scenarios such as minerals, building materials, cold chain and container transportation needs.
3. Deployment mode: A mobile base station vehicle can support 2 to 4 electric heavy trucks at the same time to replenish energy on the go.
4. Battery swapping mode: It is mainly based on the independent docking and plugging of the flight battery, combined with the positioning of the slide rail or the auxiliary operation of the robotic arm.
5. Operating mechanism: When the battery level of a truck drops to a set threshold (such as 20%), the system automatically dispatches the flight battery to dock and replenish the energy.
6. Battery recycling: The flight battery automatically returns to the base station after completing the mission to be recharged and prepared for the next mission.

The system is expected to break the traditional ground energy replenishment mode of "car parking, people, etc.", realize the uninterrupted operation of electric heavy trucks, greatly improve transportation efficiency, and provide new technical paths and ideas for the construction of an air-ground integrated logistics system in the future. (Titus *et al.*, 2022)

Application Scenario Assumption

Combined with the specific application scenarios and the core needs of users, the flight battery energy replenishment system needs to have a number of key functions in the design, and is supported by a series of modules, mainly including the following aspects:

As a refueling unit with flight capability, the flight battery should be able to complete vertical take-off and landing, short-distance cruising and automatic path planning. Through GPS, Beidou and IMU integrated navigation systems, real-time positioning and dynamic tracking of electric heavy trucks are realized, and centimeter-level precision control is completed when approaching docking, and at the same time, it has basic obstacle avoidance functions to ensure flight safety.

The scheduling of the energy replenishment task will be completed by a set of intelligent systems, which will automatically match the most suitable flight battery module according to the remaining power, driving route and logistics time of each vehicle. At the same time, the system supports multi-vehicle collaborative energy replenishment, and has a management mechanism of prioritization, path avoidance and power replenishment queue to improve the overall response efficiency.

The rear end of the whole system relies on a mobile UAV base station with traction capacity, and the modified electric heavy truck head is the platform foundation, and the vehicle is equipped with multiple standardized battery compartments, slide rail devices, power grid interfaces and battery management systems (BMS) to support complete closed-loop operations such as charging, cooling, dispatching and health status management of flight batteries.

In order to ensure the reliability of the long-term operation of the system, the flight battery body should be embedded with sensors such as temperature, voltage, and current, and have the ability to protect itself and upload data. The flight platform should also support functions such as obstacle avoidance algorithms, wind speed recognition, and emergency interrupt return. The whole system is equipped with a background monitoring platform, which displays the operation status, flight trajectory, alarm information and task history of each module in real time, which is convenient for remote operation and maintenance and abnormal response. (Mohanty, Goyal & Naikan, 2025)

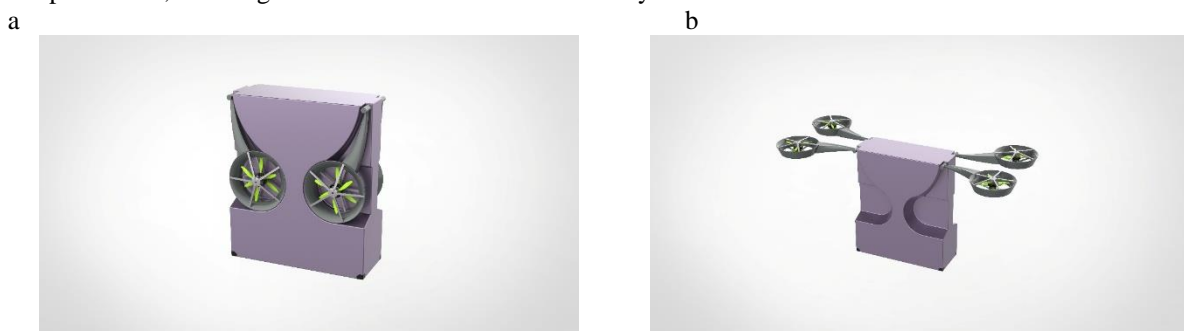
FLIGHT BATTERY AND UAV SYSTEM DESIGN

Exterior Design of the Flight Battery Module

Design language and structural beauty

As a key component of the system that frequently interacts with users and operates frequently at low altitudes, the appearance design of the flight battery module must not only meet the aerodynamic requirements, but also have a unique recognition and aesthetics. Adhering to the design concept of "functional aesthetics and streamlining", the module adopts a vertical symmetrical structure, with a tightened top and a stable load-bearing bottom, presenting a unified geometric form as a whole. Through the embedded curved surface and polygonal design, the overall sense of heaviness is effectively reduced, and the visual effect is stable and light.

Four sets of rotor folding devices are configured on both sides of the module, and the embedded structure of the robotic arm is used to realize the automatic folding and deployment of the blades. When folded (Figure 2a), the flight battery remains compact for easy transportation and storage, and when unfolded (Figure 2b), the rotor arm is extended, and the module is transformed into an air power unit, realizing the functional switch from "battery module" to "aircraft".



Source: Self-painted.

Figure 2: Flight battery blades folded and unfolded.

Material and surface craftsmanship expression

The main body of the module is made of carbon fiber reinforced composite material, which ensures good rigidity and compressive performance while reducing weight. The surface is covered with a highly wear-resistant matte coating, the main color is silver gray, and the side is equipped with a fluorescent green signal light strip, and the overall design has a sense of technology and easy recognition.

The front end of the battery module is equipped with a dynamic light ring and a status indication area, which visually displays the remaining power, connection status and flight mission progress through icons, so that users and maintenance personnel can understand the device status in real time. The top of the module is printed with a positioning QR code and a unique number, which is convenient for tracking and management in the system.

Unmanned Aerial Vehicle System Configuration Design

Multi-propeller integrated design language

In this design, the UAV adopts a four-propeller configuration, and each propeller is a coaxial dual-rotor structure, taking into account industrial aesthetics and functional integration. The quad wings are arranged symmetrically around the center, giving the overall profile a symmetrical central axis and a compact structure that allows for seamless integration with the battery module.

From a stylistic point of view, the structure exhibits a distinct "modular chimeric" character, like a group of building elements switching between different forms. The top rotor section is connected to the short arm by a circular retainer, creating a visual contrast between the "light" and "heavy" fuselage, giving the overall design tension.

The appearance is made of titanium metal coating with geometric cutting surface to enhance the scientific and technological recognition of the flight platform when working at high altitude. In view of the characteristics of frequent take-off and landing, the modular design of the fuselage is efficient, and the rotor, motor and electronic cabin all support quick disassembly and replacement, which is convenient for subsequent maintenance and upgrading. (Shahjalal *et al.*, 2022)

The color scheme is mainly matte titanium silver, which is in harmony with the material of the battery module. Night beacon lights and color recognition rings are added to the arm to improve visibility and safety management during night operations and queue flights.

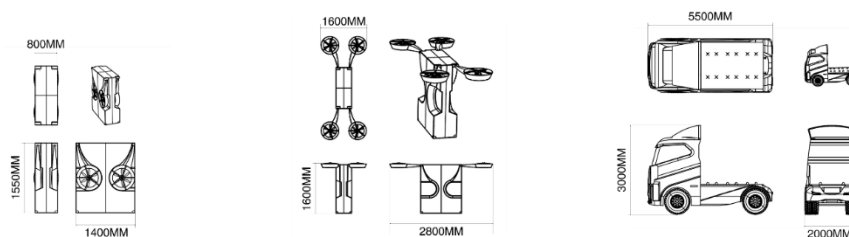
Flight platform and battery fusion design

The drone and the flight battery are not a simple combination of external plug-ins, but a "nested aircraft" with integrated structure. The flight battery not only provides energy, but also serves as the core structure of the platform, directly participating in the load-bearing and navigation of the whole aircraft. By integrating functions into the structural body, the number of connectors is effectively reduced, the potential failure rate is reduced, and the overall stability and reliability of the system are improved.

The power system adopts a four-axis coaxial configuration, and the eight rotors are combined into two sets of core power units. The flight arm is abducted to the four corners, so that the whole aircraft presents an "X" shaped tension layout when it is lifted off, which enhances the stability and recognition of the flight in terms of aerodynamics and visual perception.

Different from the traditional scheme of separating the flight platform from the energy system, the system directly integrates the flight capability into the battery module body, forming a compact logical structure of "the battery is the flight body, and the transportation is the flight mission". This design effectively reduces the size of the equipment, simplifies the operation process, eliminates the need for additional transfer platforms and supporting equipment, and is conducive to improving the operation efficiency and response speed.

When unfolded, the four corners of the battery module extend with symmetrical flight arms, each equipped with a dual counterrotor unit. By controlling the rotor angle and speed, vertical take-off and landing, stable hovering and attitude fine-tuning can be realized. The symmetrical configuration makes the flight platform more balanced when performing autonomous tasks, especially suitable for the intelligent positioning and precise landing of high-speed moving targets (Figure 3).



Source: Self-painted.
Figure 3: Three views.

Mobile Base Station System Design

Vehicle form and system visual organization

The mobile base station is based on the transformation of the heavy truck platform, and its morphological characteristics are highly integrated energy supply function, dispatching platform and transmitter in one. The overall shape maintains the heavy and stable feeling of the front of the truck, and the front face of the truck strengthens the visual impact through a highly tense bevel angle and a bright silver grille design, conveying its positioning as an "energy hub" (Figure 4).



Source: Self-painted.

Figure 4: Exterior of the mobile base station (without battery).

The overall color of the mobile base station vehicle is dark blue, combined with the silver-white metal grid structure of the front face and the yellow warning lights dotted in between, forming a visual impression with a sense of safety and power. The top of the front of the car is designed with a streamlined cockpit cover, which naturally transitions with the base of the lifting platform, which not only optimizes the wind resistance of the whole vehicle, but also enhances the overall sense of modernity of the body.

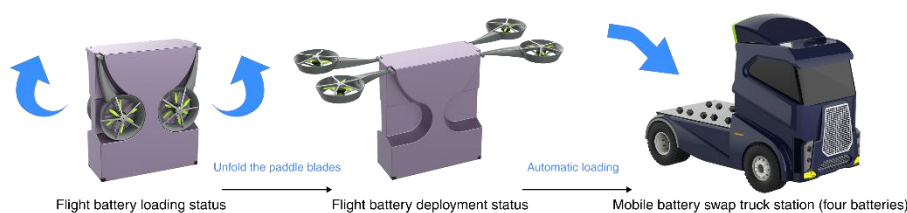
Based on the existing electric heavy-duty truck platform, the design reconstructs the appearance, and on the premise of ensuring the basic bearing and power performance, the appearance treatment emphasizes the clarity of functional distinction and the unity of visual elements, showing the sense of order and power of industrial products. The body structure is mainly divided into three functional areas:

- (1) Energy storage area (located at the rear of the vehicle): integrated multi-layer flight battery parking compartment, with a retractable robotic arm to realize automatic loading and unloading of battery modules;
- (2) dispatching central control area (located above the cockpit): antenna array and dispatching communication unit are provided inside, which are used for coordinating the flight module and vehicle information interaction;
- (3) Display and identification area (distributed on the side and top of the car body): equipped with a dynamic display screen and signal light system, which is convenient for identification and display of operation status or brand information.

The main color of the body is space blue, which conveys a sense of stability and technology, supplemented by eye-catching signal orange stripes as the functional area identification mark, which effectively enhances the visual warning in the high-speed operation environment. The front face and rear are connected by a continuous LED light strip to form the visual main line of the whole vehicle, strengthening the brand's technological attributes and sense of the future.

System integration and user experience logic

In this system, the flight battery not only exists as an energy carrier, but also assumes a key role as a medium connecting people and equipment, platforms and scenes, and is also the visual identity element of the whole system in a low-altitude environment. Through the organic integration of the flight module and the mobile base station, the product has found a balance between function and shape, and realized the comprehensive unity of design and practicality, engineering logic and formal beauty, operation efficiency and emotional experience (Figure 5). (Güven *et al.*, 2025)



Source: Self-painted.

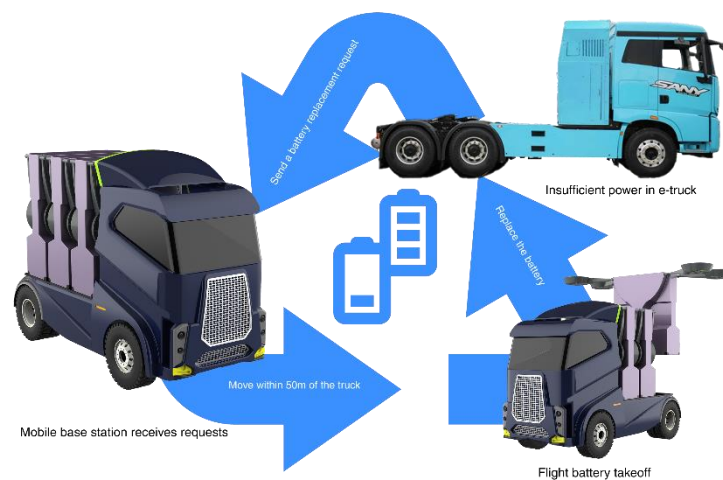
Figure 5: Mobile base station loading process.

For the driver, the system greatly simplifies the energy replenishment operation process and reduces the driving burden through automatic execution and interface visualization. For the manager, the standardized battery module and intelligent task scheduling system help to achieve efficient and controllable operation management. From a broader social perspective, this design not only has the function of use, but also stimulates the public's interest in new energy technology and low-altitude economy with its distinctive modeling language and high visibility in the aerial scene, forming a new way of energy image cognition and cultural expression.

USE PROCESS AND SCENARIO SIMULATION

The System Runs the Process

In the context of the accelerated integration of low-altitude economy and intelligent transportation, the "flight battery energy replenishment system" proposed in this design focuses on the core idea of "charging power while driving without interrupting transportation". The system cooperates with the flight control system through the intelligent dispatching platform to build a complete closed-loop energy replenishment process (Figure 6). The overall operation is divided into three main phases: pre-deployment preparation, in-flight energy replenishment, and flight battery recovery and recharging. Each stage is integrated with automatic control modules, human-computer interaction interfaces and multiple safety guarantee designs to ensure that the system has high efficiency, reliability and user-friendliness in actual operation. (El-Bayeh *et al.*, 2021)



Source: Self-painted.

Figure 6: Flowchart of energy replenishment.

Deployment Readiness Phase

Before the system is officially put into operation, a series of resource preparation and information integration work needs to be completed to ensure that each module is in good condition and has the conditions to perform the task. This phase covers the following key elements:

Path synchronization with the target: The platform is connected to the logistics system to obtain the running track and task path of heavy vehicles in real time. Combined with map information and airspace data, the optimal energy replenishment point is automatically planned to ensure the safety and efficiency of the flight process.

Battery state preparation: The mobile base station pre-charges the backup flight battery, and at the same time connects to the battery management system (BMS) for health status assessment, monitors key parameters including temperature, voltage, cycle life, etc., eliminates hidden dangers, and ensures that the flight battery is in good working condition.

Task data generation: The system automatically sets the energy replenishment threshold (the power is less than 20%) according to the remaining power of the vehicle and the operation progress. Based on this, the dispatching platform generates flight mission data packets, including take-off time, flight path, docking target and backup plan, and transmits them to the UAV control system for preload.

The core of this stage is to establish the implementation foundation of "clear status, clear path, and closed mission loop" to ensure that all links of flight, energy replenishment, and recovery can be efficiently and seamlessly connected in the future.

Replenishment Execution Phase

In the process of the system performing the energy replenishment task, the vehicle does not need to stop, and the whole process reflects the efficient operation mode of "charging while driving", which mainly includes the following steps: (Bortotti *et al.*, 2023)

Mission start: When the on-board system detects that the power level is lower than the set value (less than 20%), it will automatically send a power replenishment request, and the platform will respond immediately and dispatch the nearest available flight battery to participate in the execution.

Positioning and flight guidance: The UAV uses the Beidou positioning system and the inertial navigation (IMU) system to connect with the target vehicle for real-time positioning. At the same time, the flight rhythm is adjusted through vehicle-to-vehicle communication (V2V) technology to ensure relative position synchronization.

Dynamic access and power transmission: The flight battery docks the electric energy interface at the tail of the target vehicle through the terminal mechanical structure, and the system completes the lock identification, communication connection and energy transmission start.

Process confirmation and data archiving: After the energy replenishment is completed, both the flight platform and the vehicle confirm the task status, and the platform automatically records the flight process, power changes and equipment operation data as the basis for follow-up scheduling and system maintenance.

The core of this stage is to realize the stable flight and dynamic docking of UAVs in complex traffic environments, emphasizing the safety of the energy replenishment process, the fault tolerance of the system and the adaptability to high-frequency tasks.(Figure 7).



Source: Self-painted.

Figure 7: Diagram of the "flight battery" energy replenishment system.

CONCLUSION

In the context of increasingly severe global climate change and the continuous transformation of energy structure, electric heavy-duty trucks, as an important means to promote the transformation of green transportation, are gradually entering the forefront of application. However, traditional energy charging modes, such as fixed charging piles and centralized battery swap stations, have exposed many problems in actual operation, such as slow energy replenishment speed, high construction and maintenance costs, and lack of mobility, which seriously limit the possibility of large-scale promotion. (World Bank Group, 2022)

In order to respond to this core pain point, this paper conducts systematic design research around the concept of "flight battery energy replenishment system", and tries to propose a new energy replenishment path, in order to provide an efficient, flexible and uninterrupted energy support mode for electric heavy trucks. Based on the principle of "making the battery have flight capability", this project builds a complete technical system composed of a flight battery module, a flight platform, a mobile base station and a vehicle-air integrated dispatching system. The coaxial double-propeller flight mechanism is introduced into the platform structure, and the self-positioning energy replenishment interface and the on-board identification system are combined to realize the leapfrog innovation of the energy replenishment process from ground static to aerial dynamics.

Based on the service design methodology and integrating the holistic perspective of systems thinking, this study makes a forward-looking exploration of the possible role of flight batteries in the transportation energy system. It is expected that in the future, through continuous practice and iteration, the solution can be gradually implemented in actual operation, promote the development of green transportation in a more intelligent and efficient direction, and help build a future-oriented energy support system.

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