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Optics-driven drone

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In the field of vicinagearth security, low-altitude flying vehicles such as drones play an indispensable role in aerial remote sensing, intelligent search and rescue, etc. [1]. It can be foreseen that the autonomous and intelligent execution of complex tasks by drones is an inevitable trend for future development. However, due to the power density limitations of current chemical batteries, the endurance of drones is relatively short, which in turn limits their mission coverage radius, material delivery capacity, and information perception ability. In addition, the power supply of drones must also complete the landing and takeoff process. In fields such as power inspection and terrain mapping, frequent takeoff and landing pose a great risk of crashes and seriously affect operational efficiency. Oil-powered drones have strong endurance but poor stability, complex operation, and insufficient performance at high altitudes. Therefore, it is a major technical problem to develop a remote charging technology for drones to enhance their autonomy and intelligence during mission execution. It also has extremely high research significance and application value.

Based on artificial intelligence and laser wireless power transmission technology, this study designs an optics-driven drone (ODD) system, as shown in Figure 1. During the flight, the drone reports its position and task execution status to the ground station in real-time. When power supplementation is required, the ground station uses intelligent visual tracking and pointing algorithms to achieve stable acquisition, tracking, and pointing, and then activates the laser to deliver energy to the drone. When ODD receives the laser beam, the onboard photoelectric conversion module converts the optical energy into electrical energy, completing stable and efficient long-distance wireless energy supplementation. It is noteworthy that onboard sensors will not be affected by the laser, but their deployment location requires special consideration and must avoid the conversion module at the bottom to ensure smooth laser transmission links. The characteristics of ODD are that the energy supplementation process is synchronized with task execution and highly autonomous.

The specific challenges of ODD include target tracking, atmosphere turbulence mitigation, and obstacle perception. Advanced intelligent target tracking is a prerequisite for establishing the power supply chain of ODD. During the target tracking process, extracting the unmanned aerial vehicle (UAV) from the camera image is the most important thing. Although many target extraction techniques and methods have been developed, there are still many difficult problems to be solved due to the complex flight scenes and strong maneuverability of UAVs in this task. For example, there may be problems such as target scale changes, illumination changes, UAV rotation changes, and target occlusion during the actual target extraction process [2]. Specifically, (1) target scale changes: when using a camera to obtain image sequences, the distance between the UAV and the camera is constantly changing, which will cause the target on the imaging plane to appear in different scales. Scale changes can lead to interference with the target model, affecting the stability of the tracking algorithm and even causing the loss of the target; (2) illumination changes: as a result of the autonomous cruising capability of the drones, the illumination intensity in the scene will change greatly over time, which will cause appearance changes of the target, and even cause the loss of target features, leading to the failure of the tracking algorithm, especially in the case of strong or weak light sources; (3) target rotation changes: during the UAV's motion, rotation changes may occur, which can be divided into lateral rotation changes (around a line parallel to the image plane) and vertical rotation changes (around a line perpendicular to the image plane). Among them, the more severe one is the vertical rotation change, which may cause self-occlusion and the loss of part of the target features; (4) target occlusion: occlusion can be divided into two types, one is being occluded by other objects, and the other is self-occlusion of key features (similar to target rotation changes). Both types of occlusion can interfere with the target model, affecting the stability of the tracking algorithm and even causing tracking failure. Therefore, an intelligent target tracking algorithm that adapts to the aforementioned difficulties is the key technology for ODD.

Intelligent compensation of the atmospheric turbulence is crucial to improve the power supply efficiency of ODD. During the high-energy laser transmission process from the ground to the drone, the atmosphere covering the Earth's surface is an unavoidable transmission medium. Turbulence effects cause distortion of the laser beam wavefront, which in turn causes the intensity distribution of the beam reaching the target to continuously change [3]. When an uneven and dynamically changing intensity distribution of the laser

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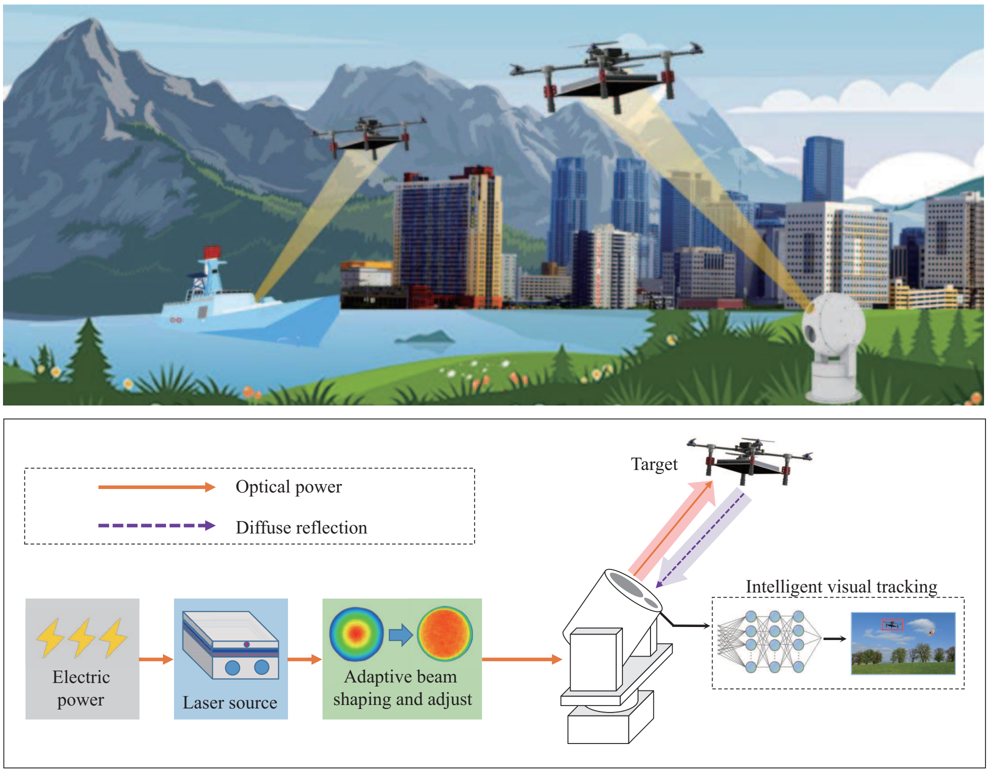

Figure 1 (Color online) Application scenarios and system composition of ODD.

beam is irradiated onto a device, the photovoltaic cell in a weak light area becomes an equivalent load, ultimately leading to the formation of a hot spot effect. This phenomenon reduces energy transmission efficiency and can even cause permanent damage to the photovoltaic cell. In theory, adaptive optics can be used to correct the high-order wavefront aberrations caused by turbulence in the laser wireless power transmission chain, thus performing adaptive correction of random changes in beam jitter, beam spreading, and intensity distribution, and improving energy transmission efficiency and reliability. However, adaptive optics systems in long-distance laser wireless power transmission chains are challenging. Especially for ODD, the chain in ODD usually operates in the low-altitude atmospheric environment with strong turbulence effects, which can cause intense flickering of the light intensity and the appearance of phase vortices in distorted wavefronts. For classical adaptive optics systems, strong scintillation and phase vortices make wavefront restoration difficult to achieve. For wavefront sensorless adaptive optics systems, although it is possible to avoid the difficulty of wavefront restoration, their turbulence compensation bandwidth is severely limited by the response rate of the controlled device, making it difficult to deal with rapid wavefront changes caused by strong turbulence effects in the laser wireless power transmission chain. Therefore, how to achieve effective turbulence compensation in a strong turbulence environment, and form a stable, dynamically controllable, and uniformly distributed energy spot with the optical axis pointing towards the energy receiver of ODD is another key technology.

Intelligent perception of obstacles along the optical beam transmission path is an important guarantee for the safety of ODD. The laser power used in ODD is usually above several hundred watts, and the energy and direction are highly concentrated. Therefore, obstacles in the link, such as pedestrians, birds, and tree leaves, may be harmed by the laser. To solve this problem, the traditional method is to first use a lower-power laser beam to scan the UAV target, then increase the laser intensity when the UAV is aligned and tracked steadily, and deliver the energy to the receiver passively. This energy transfer mode requires real-time monitoring of the laser intensity at the receiver end and maintaining smooth communication between the transmitter and receiver ends. If there is any deviation in alignment between the transmitter and receiver ends, the receiver end needs to detect it promptly and immediately notify the transmitter to stop energy emission, otherwise it can cause injury to nearby personnel or equipment damage. For low-altitude, high-speed flying UAVs, it is very difficult to maintain long-term stable alignment of the beam, the receiver's laser intensity changes rapidly, and real-time monitoring is difficult. Moreover, maintaining communication increases additional energy costs, making it less practical in actual applications. Another method to improve the safety of the laser wireless power transmission link is the distributed laser charging system (or resonant beam charging system). The implementation principle of resonant beam charging is to place a resonant cavity mirror at the transmitter end and another at the receiver end. Laser is generated in the optical resonant cavity between the two mirrors, and the laser energy collection device is placed at the output end of the resonant cavity to convert the laser energy into electrical energy output to the load. During the process of laser power transmission, if any other obstacles are suddenly placed on the line between the transmitter and receiver, the condition for laser resonance is no longer met, and energy transmission is terminated. Therefore, this system is safer than traditional laser wireless power transmission systems. However, the biggest drawback of the distributed laser charging system is that the laser beam transmission distance is relatively short, usually within tens of meters. In addition, this method requires the installation of an additional beam reflection array at the energy receiving end, which is limited in its application in ODD, where power and load weight are highly sensitive. Therefore, how to use intelligent information processing technology to dynamically perceive obstacles along the beam transmission path and adjust the laser beam's output power is a key technology in the practical process of ODD.

To solve the above problems, this study first proposes an intelligent visual tracking and pointing method. Compared with existing methods, the proposed method embeds a general lighting-sensitive module and a spatial-scale tracking module on the basis of the deep target detection model. This study uses the lighting-sensitive module to preprocess each frame of the video stream, improving the stability of the input of the tracking model. The lighting-sensitive module includes two steps, namely automatic color equalization (ACE) and adaptive contrast enhancement (ACE) that will stabilize the images of each time period to a unified lighting range. Based on this, this study inputs each enhanced frame into the spatial-scale tracking module, which takes both appearance information and previous trajectories as input to achieve robust tracking and uses a discriminative correlation filter based on pyramid representation to handle large-scale changes in complex image sequences. The parameters in the corresponding filter are updated using the target features obtained after processing, and the iterative processing ensures the accuracy of the algorithm. In addition, to mitigate the turbulence effects, this study proposes an adaptive beam shaping method based on spot-feedback reinforcement learning. When the photoelectric conversion module on the drone receives the laser beam, the on-board data acquisition card collects power data from different photoelectric conversion units and feeds this information back to the ground through the radio frequency (RF) communication link. The power distribution of different photoelectric conversion units actually characterizes the far-field intensity distribution of the beam. When this information reaches the wavefront control unit, the latter realizes the direct mapping from intensity distribution to phase distribution through an optimization control algorithm based on reinforcement learning, and then controls the wavefront corrector to achieve phase precompensation, thereby mitigating atmospheric turbulence effects through the principle of wavefront conjugation. In the end, to ensure the security of the laser link, this study proposes an occlusion detection and laser power autonomous adjustment method. First, the laser beam is encoded and modulated, and the time of flight method is used to estimate the propagation distance of the laser beam. When the laser propagation distance undergoes a sudden change, it is judged as occlusion, and the laser power is reduced or even the laser is turned off. At this time, the drone is powered by its own energy storage battery, and undergoes transitional flight until the occlusion disappears. Furthermore, to avoid the problem of erroneous tracking caused by interference from multiple target objects, the ground station continuously extracts the reflection characteristics of the target objects in real-time. By designing a recognition model for the reflection characteristics of the target objects, precise identification and correct tracking of the target objects are carried out. Experimental results show that the above techniques can effectively ensure the safety of the laser power supply and provide a stable and reliable energy source for ODD.

With the technological advantages mentioned above, ODD is expected to achieve all-day (day/night), long-distance (kilometer-level), and autonomous wireless energy supplement in the future. Based on this, ODD can undertake more complex autonomous intelligent tasks, such as autonomous simultaneous localization and mapping (SLAM) in a large-scale unknown environment. When ODD is equipped with event cameras, infrared cameras, and other sensors, their intelligent tasks can advance from daytime lighting to challenging scenarios such as low-light and night. Finally, the number of drones can evolve from single to cluster, supporting collaborative missions of drone clusters through autonomous ground-to-air, one-to-many wireless charging. In drone cluster missions, due to no need to replace batteries individually for each drone, the advantages and efficiency of the ODD system will be further amplified.

Overall, this study designs an ODD system relying on laser beams for remote power supply, including an intelligent visual tracking and pointing algorithm, an adaptive beam shaping method, and an occlusion detection and power adjustment method. Through experimental verification, the effectiveness and superiority of the proposed system are demonstrated, providing a reference for the development of drone systems in the future.

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Supporting information Videos and other supplemental documents. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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