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YingLong-SF: A Single-Rotor Foldable UAV with Morphing Center-of-Gravity

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***Abstract*—Unmanned Aerial Vehicle (UAV) demonstrates significant application potential in aerial operations and remote sensing. However, mainstream drones still face limitations in maneuverability, portability, and endurance. To address these challenges, a novel foldable single-rotor UAV named YingLong-SF (single rotor foldable) is proposed in this papper. It's mainly consist of a dynamic center-of-gravity adjustment module, a foldable attitude control module, and a foldable single-rotor module. These features reduce the folded volume to half of the deployed state, significantly enhancing portability. Additionally, the adjustable center of gravity improves wind resistance and operational controllability. Flight tests confirmed that the YingLong-SF maintains stable performance in complex airflow conditions while validating its rapid deployment capabilities, demonstrating outstanding application value in various scenarios.**

***Index Terms*—Foldable UAV, Single Rotor, Adjustable Center of Gravity.**

I. Introduction

Unmanned Aerial Vehicle (UAV) are aircraft that can achieve flight control via remote control, preset programs, or autonomous intelligent systems. Guo and his team proposed advanced robotic control strategies [1], [2], which increases the ability of drones to operate intelligently.Now UAV is capable of performing remote aerial operations and are characterized by their small size, low cost, and flexible operation. Their application range is extensive, covering areas such as military reconnaissance and emergency rescue, bringing great convenience to people's lives.

Currently, the UAV market is primarily dominated by multirotor UAV such as quadcopters and hexacopters. These multirotor UAV have a simple structure, are easy to operate and control, and offer high overall reliability. They also feature Vertical Take-Off and Landing (VTOL) capabilities and stable hovering [3]. While multi-rotor UAV undoubtedly have many advantages, they also come with several drawbacks. Firstly, studies on the aerodynamic performance of multi-rotor UAV show that their aerodynamic efficiency is poor [4], [5]. Secondly, research aimed at optimizing the energy consumption of multi-rotor UAV indicates that their energy consumption is quite high [6], [7], suggesting that their endurance is not impressive. While consuming large amounts of energy, their energy conversion efficiency is low. Due to interference between rotors, which affects the operational efficiency of UAV and reduces their wind resistance capability [8], research could focus on reducing the number of rotors to optimize flight efficiency.

Single-rotor UAV typically feature a design with a main rotor and a tail rotor, providing higher power efficiency and the ability to carry heavier payloads. Compared to multi-rotor UAV, they also exhibit better aerodynamic efficiency , [9] and can maintain stable flight even in strong winds. Helicopters are classic examples of single-rotor aircraft , utilizing a single rotor as their core component to achieve vertical takeoff and hovering capabilities [10]. Aerodynamic studies have shown that helicopters possess higher aerodynamic efficiency and outstanding maneuverability [11], capable of performing complex movements such as forward, backward, and lateral translations, along with low-speed maneuvers while maintaining a constant nose direction. This high degree of maneuverability combined with precise flight stability makes them particularly effective for landing and taking off in small areas, thereby offering a wide range of applicability.However, helicopters do have notable drawbacks: they are entirely dependent on fuel engines for power, their rotor structure generates considerable noise [12], [13],and their mechanical structure is complex, leading to high maintenance costs and poor portability. All these factors limit their application scope and usage. To overcome these limitations and combine the advantages of both types, it is necessary to design a new type of UAV.

This paper reports single-rotor foldable UAV named YingLong-SF with adjustable center of gravity.Fig. 1 shows it's work scenario.The UAV achieves active height control and precise hovering in the vertical direction through its single rotor, and employs a rudder-based attitude control module for efficient displacement via attitude adjustments. In terms of structural design, the foldable structure significantly reduces the body volume, making the UAV highly portable and quickly deployable, suitable for various complex operational environments. To verify the system's performance, blade tests and flight experiments were conducted, demonstrating that the UAV meets the expected design criteria in terms of flight stability, disturbance resistance, and three-dimensional maneuverability.The remaining content of this paper will be arranged as followed:

Section II will introduce each modules and their working principle;Section III will explain the control strategy of unmanned aerial vehicles;Section IV will analyze the experimental results of UAV;Section V will summarize the content of paper.

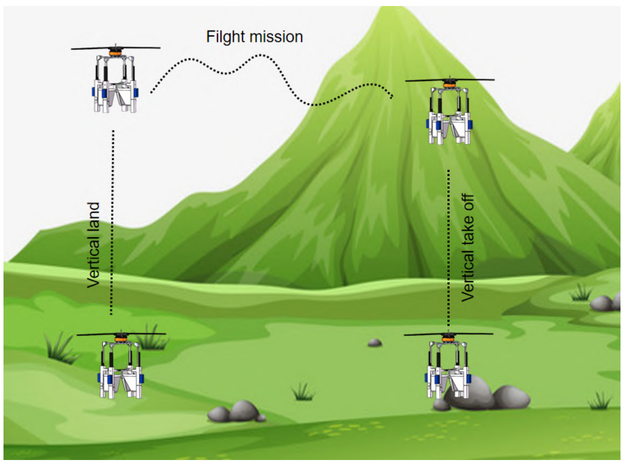

Fig. 1. YingLong-SF's work scenario

II. Prototype Vehicle Design

The entire vehicle can be divided into three parts: a dynamic center-of-gravity adjustment module, a foldable attitude control module, and a foldable single-rotor module, as shown in Fig. 2.The foldable single rotor module is connected to the top of the dynamic center of gravity adjustment module via a brushless motor, providing power for vehicle. The dynamic center of gravity adjustment module serves as the main frame of the vehicle, supplying electricity while also adjusting the vehicle's center of gravity to adapt to different working scenarios.The foldable attitude control module, installed in the middle of the dynamic center of gravity adjustment module, works with the foldable single rotor module to control the vehicle's pitch, roll, and vertical movement.

A. Dynamic Center of Gravity Adjustment Module

The adjustable center of gravity enhances environmental adaptability and mission flexibility for UAVs, yet it necessitates balancing structural complexity and control challenges. To address flight stability issues under complex airflow conditions and to mitigate structural complexity, this paper proposes a mechanically driven dynamic center-of-gravity adjustment module. As Shown in Fig. 3.The Dynamic Center of Gravity

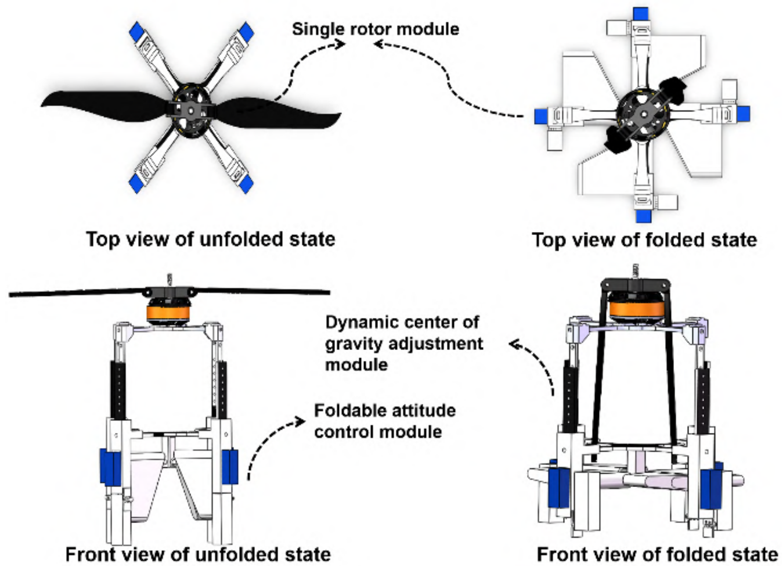

Fig. 2. Overall schematic diagram of YingLong-SF

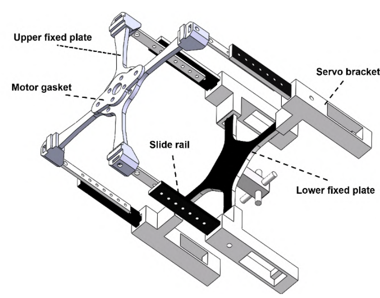

Fig. 3. Dynamic center of gravity adjustment module

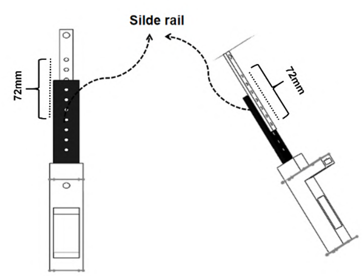

Fig. 4. Slide rail

(COG) adjustment module is primarily composed of rail structures. To reduce structural complexity while ensuring functionality, all four struts of the drone adopt this rail structure. These four rails define the drone's stability and enable the center of gravity adjustability: each rail is divided into upper and lower struts. The upper strut is connected to the upper fixed plate, whereas the lower strut is connected and secured to the servo bracket as well as the lower fixed plate. Multiple holes are drilled in the middle of the upper and lower struts and are secured with screws to form the rail structure.

As shown in Fig. 4, the rail supports an adjustable travel of 72mm, thereby achieving the function of adjustable center of gravity. Additionally, the single rotor module is connected to the upper fixed plate through a 2mm thick motor spacer. While the lower fixed plate integrates the electronic system, it is also connected to a foldable attitude control module via a rudder direction fixed plate.

Based on the aforementioned mechanical structural features, the core function of the dynamic Center of Gravity (COG) adjustment module lies in modifying the drone's mass distribution through the telescopic motion of the rail structure. As the dynamic adjustment of mass distribution directly leads to changes in the COG position, it significantly affects flight attitude and motion response. The following analysis will focus on the mechanism by which center-of-gravity positioning influences flight stability and controllability:

- **Improvement of Restoring Torque**: According to UAV's torque analysis Fig. 5.When UAV is disturbed and tilts, the restoring torque formed by gravity and lift is given by:

$$\tau_r = mg \cdot h \cdot \sin\theta \tag{1}$$

where:

  - τ_r: Restoring Torque.
  - m: Mass of the UAV.
  - g: Gravitational acceleration ($\approx 9.81\,\text{m/s}^2$).
  - h: Vertical distance from the UAV's center of gravity to the single rotor.
  - θ: Tilt angle of the UAV.

Lowering the center of gravity (reducing h) makes the response of the restoring torque more sensitive, increasing the angular acceleration:

$$\alpha = \frac{\tau_r}{I} = \frac{mgh\sin\theta}{I} \tag{2}$$

From formula 2 indicates that a low center of gravity enhances the stability of the UAV

- **Enhanced flight stability**: The aerodynamic disturbance torque under crosswind conditions is given by:

$$M_w = \frac{1}{2}\rho v_w^2 S C_m h \tag{3}$$

where:

  - M_w: Crosswind Disturbance Torque.
  - ρ: Air density (kg/m^3).
  - v_w: Wind speed (m/s).
  - S: Reference area (e.g., projected area of the UAV).
  - C_m: Moment coefficient.
  - h: Vertical distance from the center of gravity to the reference point.

Lowering the center of gravity directly reduces the wind disturbance torque, strengthen the stability when flying.

- **Impact of center of gravity on UAV operability**:

$$I = \sum m_i r_i^2 \tag{4}$$

From the formula 4, it can be inferred that if the center of gravity of the UAV is close to the axis of rotation (rudder), the mass distribution is more concentrated,$R_i$is small, and the moment of inertia Idecreases.

$$\alpha = \frac{\tau}{I} \tag{5}$$

where:

  - τ is the torque output by the motors,
  - α is the angular acceleration.

The smaller the I, the greater the angular acceleration α for the same torque, leading to faster and more responsive adjustments in the drone's attitude (pitch, roll).

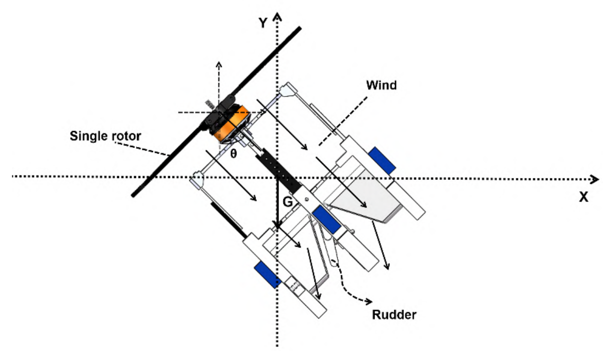

Fig. 5. Torque analysis of dynamic center of gravity adjustment module

According to the analysis, the dynamic center of gravity adjustment module allows the YingLong-SF to lower its center of gravity in environments with complex airflows, thereby enhancing the stability of the vehicle during flight. When greater maneuverability is required, the module can also raise the center of gravity to increase the vehicle's controllability.

B. Foldable Single Rotor Module

In the technological exploration of synergistic development between lightweight design and high-performance in UAV systems, rotor structure innovation has always been the core breakthrough for enhancing aircraft environmental adaptability. Therefore, compared to multi-rotor structures with inherent limitations, the YingLong-SF adopts a more efficient and quieter foldable single-rotor design.

Fig. 6. Foldable single rotor in deployed state

Fig. 7. Foldable single-rotor in folded state

As an important component of UAV, the rotor provides the necessary lift for flight. The UAV proposed in this paper adopts a foldable single-rotor structure to enhance its portability, Fig. 6 and Fig. 7 illustrate the folded and deployed states of the foldable single-rotor module, whose core comprises two carbon fiber blades (dimensions: 113 mm×25 mm, weight: 13 g) and metal blade holding mechanisms. This lightweight design ensures overall weight control while providing sufficient lift for flight. Driven by an outer-rotor brushless motor, the single-rotor can be manually controlled to statically switch and achieve a rapid conversion from a vertical folded state to a horizontal operational state within 0.5 seconds, thus enabling efficient thrust generation. Additionally, the single-rotor structure effectively reduces the drone's operational noise. The working principle of the foldable single-rotor is as follows:

In the folded state, the foldable single rotor structure allows the blades to naturally hang along the fuselage axis, reducing the storage volume of the UAV and improving its portability. During the deployment process, a single rotor can be manually deployed to provide lift for UAV.

Thrust tests were conducted on the blades using a force measurement device, and the data obtained was visualized in Fig.8. It shows that there is a significant nonlinear positive correlation between the blade rotation speed $v$and thrust F. When the rotational speed reaches its peak of 3,500 RPM, the thrust value attains 35 Newtons (N), demonstrating that the single rotor module can meet the lift requirements of VUAV and provide sufficient acceleration to ensure maneuverability.

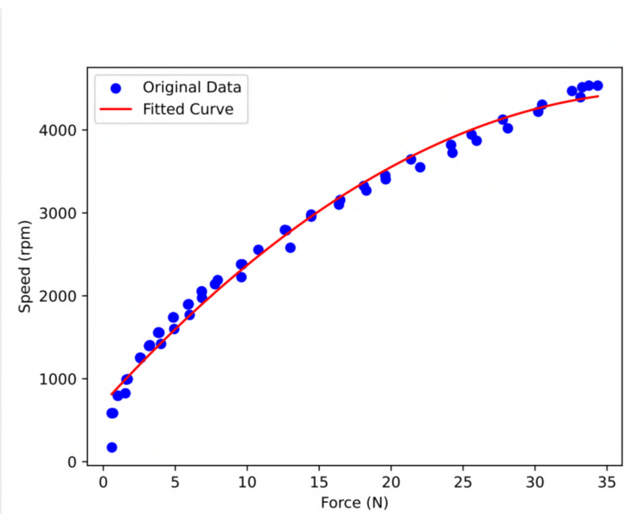

Fig. 8. Experimental results of single rotor blade thrust

C. Foldable Attitude Control Module

In order to enhance the portability of drones, this article presents a novel foldable attitude control module. This module includes four foldable support arms and four 10 kg micro servos, with each servo independently driving one control rudder. The rudder is connected to the rudder fixed plate to ensure that the rudder can rotate freely. Notably, the control rudder are made of the same lightweight material as the support arms and are designed with a hollow structure, reducing weight while maintaining strength. The working principle of the entire attitude control module is as follows:

The foldable support legs of the entire foldable attitude control module achieve folding and unfolding of the support legs through a hinge mechanism. As shown in Fig .9, when deployment is needed, the hinge mechanism drives the support legs to rotate 180 degrees clockwise until they are fully deployed, and position locking is achieved through a fixing device. In the storage state, the support legs are folded back 180 degrees opposite to the side of the servos, while at the same time the servos rotate the control surfaces 90 degrees to complete the storage configuration of the drone. This design effectively reduces the overall volume of the aircraft while ensuring system stability and reliability, greatly enhancing the portability of the aircraft.

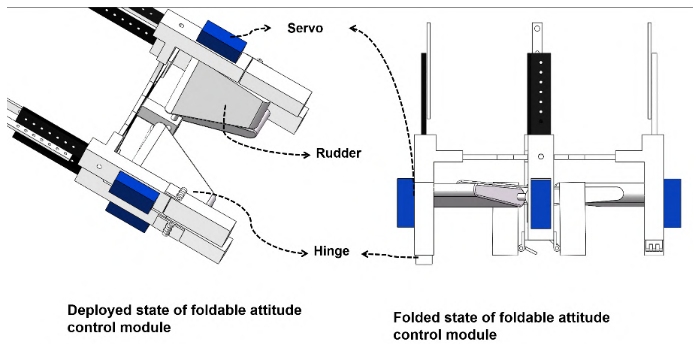

Fig. 9. Deployed state and folded state of foldable attitude control module

D. Avionics

YingLong-SF's avionics consists of a power supply, flight controller, communication module, and electronic speed controllers (ESCs), all interconnected to the flight controller via standardized interfaces. The flight controller collects real-time data on the UAV's attitude, position, environment, and operational status, while logging mission and runtime information. The dual-band (2.4GHz/433MHz) communication module enables real-time data exchange and command transmission with ground stations and remote controllers. ESCs receive PWM signals from the flight controller to precisely regulate brushless motor speeds for dynamic rotor thrust control. A four-channel PWM time-division multiplexing technology allows independent or coordinated actuation of the quad-rotor servos, achieving precise planar maneuverability. Modular design ensures rapid component replacement and upgrades, enhancing avionics maintenance and scalability efficiency.The connection between modules is shown in Fig. 10.

III. CONTROL STRATEGY

A. PID-based Motion Control

During flight operations, the YingLong-SF employs a Proportional-Integral-Derivative (PID) control strategy tailored

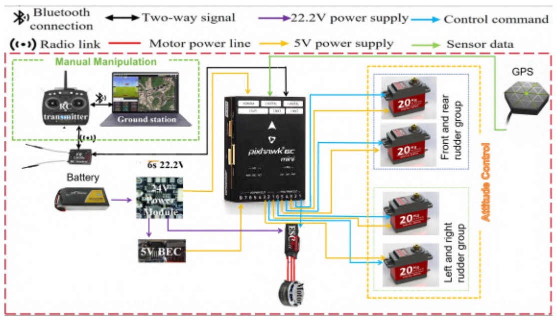

Fig. 10. The electronic layout of YingLong-SF between modules illustrates the onboard and off board components and their connections as shown in the diagram

to its single-rotor architecture. The PID controller adjusts the aircraft's attitude (pitch, roll) and yaw control via the foldable attitude control module. The PID control loop minimizes the error between desired and actual attitudes, ensuring stable and responsive flight characteristics. These PID parameters are calibrated through field experiments to achieve optimal stability, response speed, and minimum overshoot. The PID control process is as follows Fig. 11:

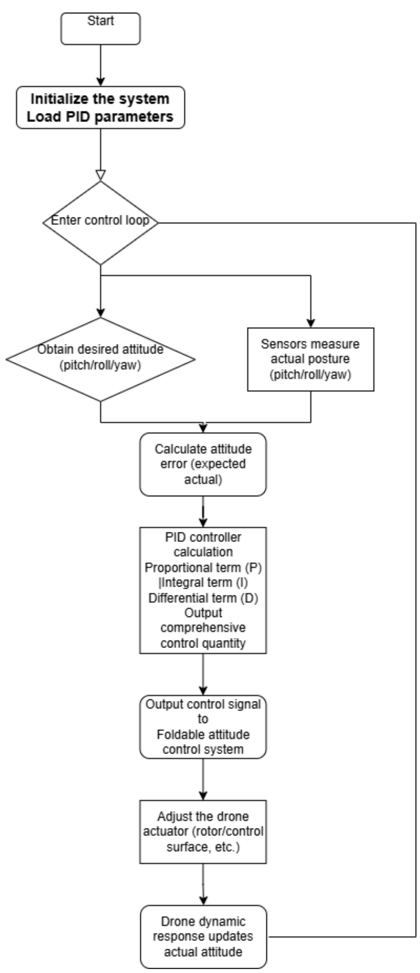

Fig. 11. PID control process

B. Attitude Control

The movement of Single-rotor UAV depends on its attitude transformation.The foldable attitude control module of YingLong-SF achieves precise horizontal movement control through paired support arms and rudders. The flight control module receives signals from the remote controller to drive the servos on each pair of support arms, actuating the rudders to deflect. The front-rear rudder group adjusts the drone's pitch angle to control longitudinal motion, while the left-right rudder group modifies the roll angle to enable lateral movement. As shown in Fig. 12, when the control rudders deflect to specific angle θ, aerodynamic forces alter the drone's attitude, enabling it to move precisely in the direction aligned with its body orientation.

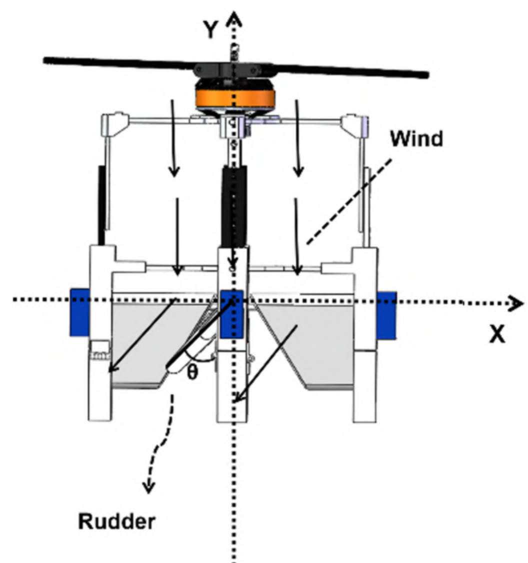

Fig. 12. Benefit analysis of rudder

IV. Flight Experiment

To verify the feasibility of the Yinglong-SF design, the team conducted flight experiments to evaluate its performance shown as Fig. 13. Several key indicators from the experimental results show that the design possesses good responsiveness and controllability:

During the flight, the attitude change curves for Pitch and Roll: Fig. 14 and Fig. 15 show that they can closely follow their respective target values. As shown in TABLE. I the roll and pitch attitude tracking error of UAV during flight is within 5 °, while the attitude tracking error of Yaw is within 10 °. This means that when performing complex maneuvers, Yinglong-SF is able to maintain the expected attitude, which is essential for ensuring flight stability. The result also validate the flight stability and three-dimensional spatial maneuverability of Yinglong-SF.

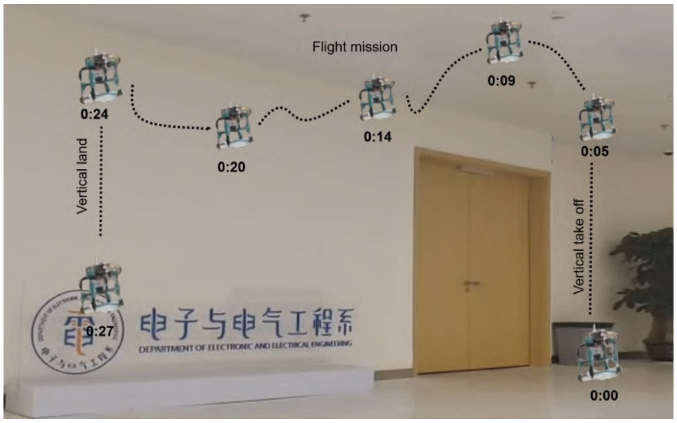

Fig. 13. Flight experiment

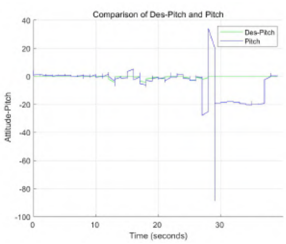

Fig. 14. Flight experiment's attitude-Pitch's variance

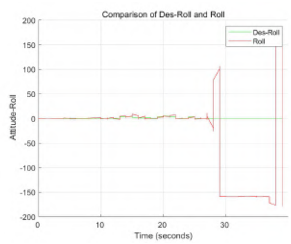

Fig. 15. Flight experiment's attitude-Roll's variance

V. Conclusion

This paper presents a novel foldable single-rotor UAV with adjustable center of gravity, named Yinglong SF, which addresses the limitations of traditional multi-rotor UAVs and helicopters in maneuverability, portability, and endurance through three core innovations. Dynamic COG Adjustment Module: A multi-stage telescoping slide rail structure enables real-time modification of the UAV's center of gravity by adjusting the relative positions of the motor and attitude control modules. This system lowers the center of gravity to enhance stability via increased aerodynamic resistance or raises it to reduce rotational inertia, accelerate attitude response, and improve control precision. Foldable Single-Rotor module: The collapsible rotor design enhances portability, improves energy efficiency, minimizes aerodynamic interference, and reduces power consumption and noise.Foldable Attitude Control Module: This mechanism ensures agile maneuverability while further optimizing compact storage.Flight experiments have validated the UAV's controllability, maneuverability, and stability in complex environments, demonstrating its broad potential for engineering applications.Key performance parameters included in TABLE. I.Future research will focus on developing Yinglong SF for cross-medium operations to expand its operational versatility.

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TABLE I
YingLong-SF: Aircraft parameters

Metric	Value
UAV Name	YingLong-SF
Attitude Tracking Error	$\leqslant 5°$ (Roll/Pitch), $\leqslant 9.61°$ (Yaw)
Weight (with battery)	430g
Flight Time	$\approx 7mins$
Dimensions (Unfolded)	Radius: 113 mm, Height: 225 mm
Dimensions (Folded)	125 mm $\times$ 125 mm $\times$ 180 mm

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