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Design and Implementation of Modular Payload Device for Precise Grasping and Throwing of Low-Altitude UAVs

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Abstract: *Aiming at the problems including insufficient versatility, poor grasping stability and low flight-control coordination of payload devices in UAV material transportation under the background of low-altitude economy, this paper designs and implements a modular payload device for precise grasping and throwing of low-altitude UAVs. Adopting a hierarchical architecture consisting of four modules: grasping module, connection module, driving module and control module, the device realizes uniform-force grasping via symmetric dual-servo-driven grippers. A cross-shaped shock-absorbing connection bracket guarantees flight stability. Moreover, a signal coordination link is established between a miniaturized single-chip microcomputer and the Pixhawk flight controller to realize the automated workflow of "grasping confirmation — flight initiation — precise throwing". Key mechanical parameter calculation, SolidWorks 3D modeling and motion simulation, structural static analysis and forming via PLA+carbon-fiber composite material 3D-printing are completed. Experiments show that the device can stably grasp a standard sandbag of 130 mm×130 mm×130 mm with a mass of 1 kg and provides sufficient grasping-force margin. The UAV presents smooth attitude response after mounting this device. It can provide a feasible technical solution for low-altitude operation scenarios such as emergency rescue and urban logistics.*

Keywords: quadrotor UAV; modular payload device; precise grasping; servo drive; flight-control coordination; 3D-printing

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I. Introduction

In recent years, as a strategic emerging industry, the low-altitude economy has achieved rapid development. UAVs are increasingly applied in material transportation, emergency rescue, urban logistics and other fields, putting forward higher requirements for the functionality and practicality of UAV payload devices[1]. Traditional quadrotor UAVs are mostly limited to passive interaction scenarios such as aerial photography and inspection. Lacking the capability of active interaction with physical environments, they can hardly satisfy the practical demands for precise grasping and delivery of materials[2].

Plenty of research has been carried out by domestic and foreign scholars in the field of UAV active operation. Chen Guangsheng[2] designed a flexible three-fingered soft gripper based on the fin-ray effect, established the grasping dynamic model of quadrotor UAV under centroid offset, and proposed a model-reference adaptive control strategy. The attitude stability during grasping was verified through ROS and Gazebo simulation. Targeting industrial robot handling scenarios, Zang Huan et al.[3] designed an adaptive control system for four-fingered flexible grippers with pressure feedback. Taking the STC8H1K08 single-chip microcomputer as the main controller, it dynamically adjusts PWM driving signals by real-time perception of grasping force via pressure sensors, so as to realize stable grasping of objects with different sizes and materials. Oriented to forest-fire rescue scenarios, Chen Haoju et al.[4] constructed a precise material delivery system based on the Pixhawk flight controller, PX4Flow optical-flow sensor and intelligent servo gripper. Its average static delivery error reaches 0.25 m, and the overall delivery accuracy hits 95%.

The above studies have advanced UAV operation technology from perspectives of flexible gripper structure, force-feedback control and precise delivery system. Nevertheless, deficiencies still exist: first, most payload devices adopt special-purpose design with high inter-module coupling, which makes it difficult to rapidly adapt to different operation tasks; second, single-servo schemes are widely adopted for grasping drive, and uneven stress tends to cause swinging or even falling-off of objects during grasping; third, the coordination level between flight controllers and payload devices is relatively low, lacking linkage between grasping-state feedback and automated operation workflows. To solve these problems, this paper designs a modular payload device for precise grasping and throwing of low-altitude UAVs. It adopts a four-module hierarchical architecture, improves grasping stability through symmetric dual-servo driving, realizes automated operation

workflow linkage via grasping-in-place detection sensors and flight controllers, and completes rapid prototyping and verification with digital design and 3D-printing technology.

II. Overall System Design

2.1 Design Requirements and Technical Indicators

Mounted on quadrotor UAV platforms and oriented to low-altitude material-transport scenarios, this device undertakes the core task of precise grasping and throwing of standard sandbags. Design requirements cover function, structure and innovation. In terms of function, it shall stably grasp 130 mm×130 mm×130 mm sandbags weighing 1 kg and cooperate with UAVs to complete precise throwing. Structurally, the device shall be mounted underneath UAVs with compact and reasonable layout without interfering with UAV take-off, landing and flight attitude. For innovation, breakthroughs shall be achieved in structural design, driving mode or control logic to enhance operation efficiency and reliability. Major technical indicators are shown in Table 1.

Table 1. Major technical indicators of the device

Indicator Item	Parameter Value
Target grasped-object size	130 mm×130 mm×130 mm
Mass of target grasped object	1 kg
Maximum gripper opening-closing stroke	150 mm
Gripper opening-closing angle range	30°～120°
Torque of single servo	2.5 kg·cm
Mass of single servo	20 g
Height of connection bracket	80 mm
Total mass of device (excluding sandbag)	Approx. 0.3 kg
Centroid offset	≤5 mm
Control mode	Manual remote control / Preset program

2.2 Overall Modular Architecture

Following the concept of modular design, the whole device is divided into four core parts: grasping module, connection module, driving module and control module. Mechanical and electrical connections between modules are realized through standardized interfaces for convenient maintenance, replacement and function expansion.

Located at the bottom of the device, the grasping module directly performs object clamping and adopts a symmetric dual-gripper structure with anti-slip rubber pads laid on inner sides to increase friction. Situated between the UAV and the main gripper body, the connection module is bolt-fixed to mounting holes at the UAV bottom via a cross-shaped bracket, and vibration-damping rubber pads are installed to isolate flight vibration. Taking two miniature digital servos as power sources, the driving module drives opening and closing of grippers on both sides through servo arms and linkages. Centered on a miniaturized single-chip microcomputer, the control module builds serial-port communication with the UAV flight controller to receive grasping/throwing commands, outputs PWM signals to drive servos, collects signals from grasping-in-place sensors and feeds them back to the flight controller, forming a complete closed-loop control.

Table 2. Functions and structural-design essentials of four modules

Module	Core Function	Structural-design Essentials
Grasping Module	Clamp and release objects	Symmetric dual grippers, inner anti-slip rubber pads, arc-shaped tips
Connection Module	Connect UAV and gripper main body, damp vibration	Cross-shaped bracket, bolt fastening, vibration-damping rubber pads, height 80 mm
Driving Module	Supply power for gripper opening-closing	Dual miniature digital servos, servo-arm plus linkage transmission
Control Module	Command parsing, servo driving, state feedback	Single-chip-microcomputer main control, serial-port communication, PWM output, sensor acquisition

III. Mechanical-Structure Design and Mechanical Analysis

3.1 Grasping-Module Design

The grasping module adopts a symmetric dual-gripper structure. Compared with traditional single-gripper or eccentric-gripper schemes, the symmetric layout distributes clamping force evenly on two sides of an object and prevents tilting or slipping caused by unilateral stress. Detachable anti-slip rubber pads are installed on inner gripper sides. Given a friction coefficient of 0.4 between rubber and fabric contact surfaces, friction with sandbags is greatly increased to avoid downward sliding during grasping. Gripper tips adopt arc transitions to better fit outer contours of sandbags, enlarge contact areas and improve grasping stability. The effective gripper grasping length is set as 140 mm to fully wrap side surfaces of 130-mm-side-length sandbags. Its opening-closing angle ranges from 30° to 120°, corresponding to a maximum opening-closing stroke of 150 mm, satisfying grasping requirements for target objects. The detachable anti-slip rubber pads allow replacement of adaptive cushion materials for different supplies, improving device versatility.

3.2 Connection-Module Design

The connection module is designed as a cross-shaped connection bracket bolt-fastened to mounting holes at the UAV bottom. Vibration-damping rubber pads made of natural rubber with Shore hardness 30 are installed between the bracket and the main gripper body, which effectively attenuate transmission of high-frequency vibration generated during UAV flight toward the gripper device and reduce clamping-force fluctuation and object loosening induced by vibration. The bracket height is set as 80 mm through trade-off analysis: it ensures that the device bottom will not block UAV propeller airflow fields and interfere with normal take-off and landing, while avoiding excessive downward centroid shift caused by an over-high bracket that would degrade flight maneuverability. Made of PLA+carbon-fiber composite material, the bracket balances lightweight property and structural strength.

3.3 Driving-Module Design

Two miniature digital servos weighing merely 20 g are selected as power sources of the driving module to independently drive motions of grippers on both sides. Compared with traditional single-servo schemes using gear-group linkage, the symmetric dual-servo driving scheme boasts the following advantages: first, forces on grippers of two sides are independently controllable for better grasping symmetry; second, complex gear transmission mechanisms are eliminated, leading to simpler structures, higher transmission efficiency and easier maintenance; third, even if one servo fails, the other can still provide partial clamping force and improve system redundancy. With a rated torque of 2.5 kg·cm, the selected servos are verified by mechanical calculation to overcome gravity and friction of 1-kg sandbags and realize stable grasping. Servos are connected to gripper linkages via servo arms, converting rotary motions of servos into opening-closing motions of grippers with simple and efficient transmission structures.

3.4 Key Mechanical Calculation

Gravity of the sandbag: $G=mg=1\ \text{kg} \times 9.8\ \text{m/s}^2=9.8\ \text{N}$. The friction coefficient μ between anti-slip rubber pads on gripper inner sides and sandbag fabric is taken as 0.4. According to static-friction equilibrium conditions, to prevent vertical downward sliding of sandbags, the minimum unilateral grasping force satisfies $2\mu F \ge G$, i.e. $F \ge G/(2\mu)=9.8/(2\times0.4)=12.25\ \text{N}$. Considering acceleration disturbance and attitude tilting during flight, a safety factor of 2 is adopted, and the required unilateral grasping force is approximately 24.5 N. After force amplification by linkages, each selected miniature servo can output a clamping force above 25 N. Jointly operated by two servos, sufficient grasping-force margin is guaranteed for stable grasping under flight disturbance.

The connection bracket shall bear total gravity of the gripper device self-weight (approx. 0.3 kg) and sandbag (1 kg). Total load: $F_\text{total}=(0.3+1)\ \text{kg} \times 9.8\ \text{m/s}^2=12.74\ \text{N}$. Made of PLA+carbon-fiber composite material, the bracket has tensile strength $\sigma=50\ \text{MPa}$. According to strength condition $\sigma=F/S$, the minimum required area joints between the bracket and servo mounting seats. Local thickness is increased from 3 mm to 4 mm for these positions to further lower stress levels.

The gripper opening-closing stroke is calculated via trigonometric functions: $\text{Stroke}=2L\sin(\theta/2)$, where L denotes the effective gripper length (140 mm) and θ denotes the opening-closing angle. When $\theta=120^\circ$, the theoretical maximum stroke equals $2\times140\times\sin60^\circ\approx242\ \text{mm}$. Restricted by mechanical limits, the actual effective stroke is 150 mm, meeting grasping requirements for 130-mm-side-length sandbags. The centroid position is calculated using the mass-attribute function in SolidWorks. By adjusting connection-bracket height and layout of each module in design, the overall device centroid is guaranteed to vertically coincide with the UAV mounting point, with horizontal offset controlled within 5 mm, avoiding UAV flight-attitude imbalance induced

by centroid offset. Relevant research[2] indicates that centroid offset after payload mounting acts as a key factor affecting UAV attitude stability. Strict control over centroid offset is critical to flight safety.

IV. Control-System Design

4.1 Hardware Design of Control Module

Centered on a miniaturized single-chip microcomputer, the control module receives flight-controller commands, drives servo motions and collects sensor signals. It communicates with the UAV flight controller via Universal Asynchronous Receiver-Transmitter (UART) to receive task commands such as grasping and throwing; generates adjustable-duty-cycle PWM signals through timers and outputs them to servos to control gripper opening-closing angles and speeds; collects analog signals from grasping-in-place detection sensors through Analog-to-Digital Conversion (ADC) channels to judge whether grippers fully clamp objects. Two control modes are supported: manual remote-control mode and preset-program mode. Under manual mode, operators directly trigger grasping/throwing actions via remote controllers. Under automatic mode, the flight controller automatically issues commands according to preset flight routes and waypoint coordinates to realize full-process unmanned operation.

In terms of force-feedback control, the adaptive-control scheme with pressure feedback from Reference [3] can be referenced. Pressure-sensor arrays are integrated on inner gripper sides to collect real-time clamping-force data. PID algorithms dynamically adjust PWM duty cycles to realize hierarchical control of "light-contact pre-clamping — adaptive force application — stable clamping", which ensures reliable grasping while avoiding damage to object surfaces caused by excessive grasping force. In the current version of this device, grasping-in-place detection sensors are used to confirm clamping status. Pressure-feedback channels can be expanded in follow-up work to further improve precise control of grasping force.

4.2 Flight-Controller Integration and Signal Connection

Adopting the Pixhawk open-source flight controller running ArduPilot firmware, the flight-control system possesses mature functions for attitude control, navigation-positioning and task management. Three signal paths are built between the control module and the flight controller, as shown in Table 3.

Table 3. Signal connection between control module and flight controller

表格

No.	Signal Source	Signal Target	Function
1	Control-module TX	Flight-controller Aux1 (RX)	Receive grasping / throwing commands from flight controller
2	Grasping-in-place-sensor output	Flight-controller Aux2 (digital input)	Feed back grasping status
3	Control-module PWM output	Servo PWM input	Drive servo actions

The TX pin of the control module (single-chip microcomputer) is connected to Aux1 (RX) pin of the flight controller for receiving grasping/throwing commands issued by the flight controller. Output pins of grasping-in-place sensors are connected to Aux2 (digital input) pin of the flight controller to feed grasping status back to the flight controller. PWM-input pins of servos are connected to PWM-output pins of the control module, and servos are driven by the control module. This connection scheme forms a three-level signal link: flight controller — control module — actuators. Grasping status is directly fed back to the flight controller, providing status basis for automated task workflows.

4.3 Parameter Configuration and Control Strategy

After mounting the payload device, total mass and moment of inertia of the UAV change, so original PID parameters become inapplicable and shall be re-tuned. After repeated debugging, attitude-control PID parameters are set as: proportional coefficient \(P=4.0\), integral coefficient \(I=0.5\), differential coefficient \(D=0.2\). This set of parameters ensures moderate attitude-response speed of the UAV after device mounting without obvious overshoot or shaking. Research in Reference [2] shows that for quadrotor UAVs equipped with grippers, Model-Reference Adaptive Control (MRAC) delivers stronger anti-disturbance capability and better tracking performance than traditional PID under centroid-offset and force-disturbance conditions. Adaptive control algorithms can be introduced in follow-up work to further improve attitude stability during payload-carrying flight.

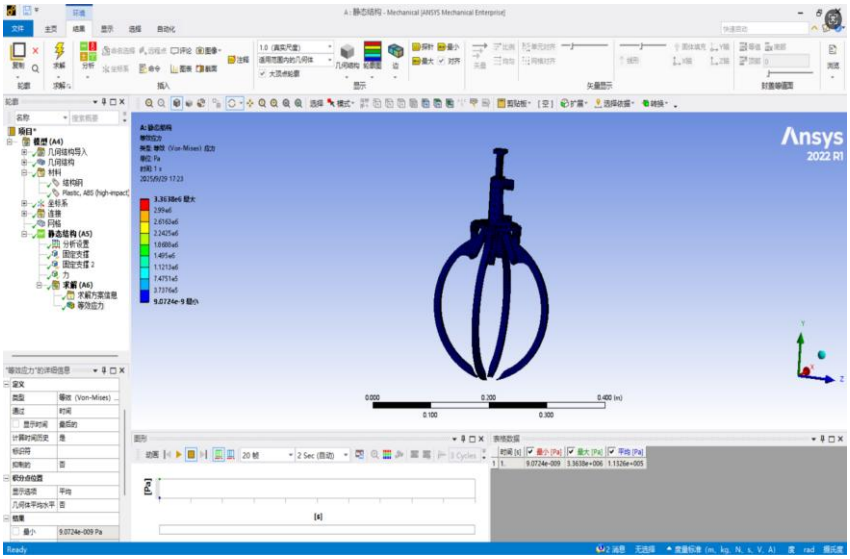
In ArduPilot firmware, the task mode is set as "auto-throw". Latitude-longitude of grasping points, flight routes and latitude-longitude of throwing points are preset. The UAV autonomously flies above the grasping point according to GPS positioning. After stable hovering, it issues grasping commands to the control module via Aux1. The control module drives servos to clamp sandbags. After grasping-in-place sensors are

triggered, “grasping completed” signals are fed back to the flight controller via Aux2. Upon confirmation of successful grasping, the flight controller initiates flight and flies along preset routes to above the throwing point. After hovering stably again, it issues throwing commands. The control module drives grippers to open and release sandbags, completing precise throwing. This automated workflow of “grasping confirmation — flight initiation — precise throwing” effectively reduces human-operation errors and improves throwing accuracy.

Multiple safety-protection mechanisms are configured to guarantee flight safety. Low-battery protection: automatic return-to-home is triggered when remaining battery capacity drops to 20 % to prevent crash caused by battery exhaustion. Attitude-abnormality protection: automatic hovering is activated when the UAV tilt angle exceeds 30° to avoid out-of-control risks induced by device faults or airflow disturbance. Grasping-failure protection: if no grasping-in-place feedback signal is received within 5 s after the flight controller issues grasping commands, grasping failure is judged. The flight controller keeps hovering and waits for manual intervention, eliminating potential safety hazards brought by flight with incompletely clamped objects. Similar multi-sensor-fusion and safety-protection strategies are adopted in the forest-fire-rescue material-delivery system described in Reference [4], which verifies the effectiveness of such mechanisms in complex environments.

V. Digital Design, Processing and Manufacturing

3D modeling and overall assembly of four modules are completed in SolidWorks software. Part dimensions are strictly determined according to design parameters in modeling. Motion constraints are defined via assembly mates to guarantee kinematic correctness of the assembly body. The SolidWorks Motion module is adopted for motion simulation to simulate the whole gripper opening-closing process and stress conditions of the device under flight states. Simulation results show that grippers finish full-stroke movements within merely 0.3 s in the initial design, which generates severe shaking of sandbags the moment clamping is completed and brings falling-off risks. Servo driving parameters are adjusted accordingly, and the gripper opening-closing duration is set to 0.8 s. Higher smoothness of clamping motions is achieved by lowering action speed.



The SolidWorks Simulation module is used for structural static analysis of connection brackets and main gripper bodies. Total load of device self-weight plus sandbag (12.74 N) is applied, and bolt holes for bracket-UAV connection are set as fixed constraints. Analysis results reveal stress concentration at joints between the bracket and servo mounting seats, where maximum stress exceeds allowable material stress. To solve this problem, wall thickness of key loaded positions is increased from 3 mm to 4 mm, and fillet transitions are added at corners to mitigate stress concentration. Static analysis is re-executed after optimization. The maximum stress drops below allowable material stress, satisfying structural-strength requirements under flight loads.

Main structural parts are made of PLA+carbon-fiber composite material. With a density of only 1.2 g/cm³, this material achieves 30 % higher strength than ordinary PLA. It delivers favorable 3D-printing formability and high surface precision, and meets dual requirements of lightweight property and strength for UAV payload devices. For auxiliary materials: anti-slip rubber pads are made of silicone rubber with Shore hardness 50, balancing friction performance and wear resistance; vibration-damping rubber pads adopt natural

rubber with Shore hardness 30 for good damping characteristics; servo connecting wires are wear-resistant silicone wires.

A desktop FDM 3D-printer is used for manufacturing with printing precision set to 0.1 mm. Core process parameters: layer height 0.15 mm, infill density 60 %, printing speed 50 mm/s, nozzle temperature 210 ℃, hot-bed temperature 60 ℃. Support structures with 20 % support density are adopted for key stressed components such as grippers and connection brackets to guarantee forming quality of overhanging structures. Supports are removed after printing, and assembling surfaces are polished to ensure fitting precision.

Component assembly follows the sequence: connection bracket → driving servos → gripper linkages → control module → sensors. First, the cross-shaped connection bracket is bolt-fastened to the UAV bottom with vibration-damping rubber pads installed. Next, two servos are mounted on servo seats of the bracket, and servo arms are connected to gripper linkages. Then left-right grippers are assembled, and servo strokes plus gripper opening-closing angles are debugged to ensure synchronous and smooth motions of grippers on both sides. Afterwards, circuit boards of the control module are installed, and servo signal wires, sensor wires and flight-controller communication wires are connected. Finally, grasping-in-place detection sensors are mounted and their trigger positions are adjusted. Ground joint commissioning is conducted after assembly to verify normal grasping motions, reliable sensor feedback and valid flight-controller communication. Servo median positions and stroke parameters are fine-tuned according to test results.

VI. Experimental Tests and Result Analysis

Mounted underneath the UAV fixed on a ground fixture, the device is tested for ground grasping. Test objects are standard sandbags (130 mm×130 mm×130 mm, 1 kg). Test contents cover smoothness of gripper opening-closing motions, trigger reliability of grasping-in-place sensors, clamping stability of sandbags and repeatability of continuous grasping. Test results show that grippers complete opening-closing motions stably within 0.8 s without jamming or abnormal noise. Grasping-in-place sensors are reliably triggered upon full gripper clamping with stable feedback signals. Sandbags stay clamped without slipping under manually applied vertical disturbance. In 20 consecutive grasping tests, the grasping success rate reaches 100 %, verifying static grasping reliability of the device.

Short-range flight tests are performed in open outdoor sites to verify influences of the mounted device on UAV flight performance. Test items include hovering stability, point-to-point flight accuracy, attitude-response characteristics and sandbag-clamping status during flight. After mounting the device and sandbags, the total take-off mass of the UAV reaches approximately 3.0 kg. Under PID parameters (\(P=4.0\), \(I=0.5\), \(D=0.2\)), the UAV can hover stably with attitude-angle fluctuations within normal ranges and without obvious oscillation. It accurately tracks preset waypoints during point-to-point flight with smooth flight trajectories. Sandbags remain firmly clamped without loosening or falling-off throughout flight. Test results demonstrate that the modular design and vibration-damping connection scheme of the device effectively guarantee mounting-flight compatibility and stability.

Precise-throwing tests are carried out under automatic-task mode. Grasping-point and throwing-point coordinates are preset via the QGroundControl ground station. The UAV autonomously completes the whole workflow: take-off — fly to grasping point — grasp sandbag — fly to throwing point — throw sandbag — return-to-home. A circular target with a diameter of 1 m is set at the throwing point. The distance between sandbag landing points and the target center serves as the evaluation indicator for throwing precision. Referring to test methods from similar research[4], tests are conducted under static hovering-throwing and low-speed dynamic-flight-throwing conditions. Test results indicate that sandbags land within the target under static hovering-throwing conditions, and throwing precision satisfies design requirements. Under low-speed dynamic-flight conditions, throwing errors increase due to initial velocity of sandbags brought by UAV forward movement. Advance-quantity delivery algorithms can be introduced in follow-up work to further optimize dynamic-throwing precision.

VII. Conclusions and Prospects

This paper designs and implements a modular payload device for precise grasping and throwing of low-altitude UAVs. Major work and conclusions are summarized as follows:

(1) A four-module hierarchical architecture consisting of grasping module, connection module, driving module and control module is proposed. Modules are connected via standardized interfaces with favorable maintainability and expandability. The symmetric dual-servo driving scheme delivers more uniform stress and significantly improves grasping stability compared with traditional single-servo driving.

(2) Key-mechanical-parameter theoretical calculation is completed, including grasping force, structural strength, dimensional parameters and centroid position. Calculation results demonstrate sufficient grasping-force margin, qualified structural strength and centroid offset controlled within 5 mm, providing theoretical basis for design.

(3) A signal coordination link between the control module and Pixhawk flight controller is established. Grasping-in-place-sensor feedback realizes the automated workflow of "grasping confirmation — flight initiation — precise throwing". Multiple safety-protection mechanisms are configured, including low-battery protection, attitude-abnormality protection and grasping-failure protection.

(4) 3D modeling, motion simulation and structural static analysis are accomplished using SolidWorks. Optimizations are conducted aiming at excessive gripper opening-closing speed and bracket stress concentration found in simulation. The device is manufactured via 3D-printing with PLA+carbon-fiber composite material. Ground grasping tests, flight-compatibility tests and precise-throwing tests verify the feasibility and reliability of the device.

Follow-up research can be expanded in the following directions. First, machine vision and AI target-recognition technology can be introduced to realize automatic identification, positioning and grasping of supplies with diverse shapes and sizes, improving autonomous operation capability of the device in unknown environments. Second, pressure-sensor arrays shall be integrated. The pressure-feedback adaptive-control scheme from Reference [3] can be referenced to realize precise closed-loop control of grasping force and adapt to more materials and fragile objects. Third, standardized quick-change interfaces shall be developed to build a universal payload platform compatible with multiple functional modules such as precise launchers, high-definition cameras, gas sensors and mapping radars for multi-purpose utilization of one UAV. Fourth, aviation-grade carbon-fiber composite materials and topology-optimization design can be adopted to further reduce device weight and increase payload capacity and endurance. Fifth, advanced algorithms such as model-reference adaptive control[2] shall be introduced to improve attitude stability of payload-carrying flight under centroid offset and external-force disturbance.

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