International Core Journal of Engineering
ISSN: 2414-1895

Volume 10 Issue 6, 2024
DOI: 10.6919/ICJE.202406_10(6).0001

Key Technologies and Development Trends of Catapult Launched Foldable Unmanned Aerial Vehicles

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Abstract

The catapult launched foldable drone is a new type of aircraft that combines catapult launch technology and folding technology based on traditional drones. It has the potential for mass transportation after folding, cluster launch of mobile carriers, and rapid deployment in special battlefield environments. It has potential application value in both military and civilian fields. This article first introduces the current development status of two types of catapult launched foldable drones, including fixed wing and rotary wing, and focuses on analyzing their key technologies such as folding technology, catapult launch technology, and stability enhancement control technology. Finally, the application prospects of catapult launched foldable drones are discussed, and thoughts on future development are given.

Keywords

Foldable UAV; Folding Technology; Launch Technology; Control Technology.

1. Introduction

In the trend of increasing unmanned and intelligent development on today's battlefield, unmanned aerial vehicles (UAVs) have played a significant role as efficient and flexible unmanned flight platforms [1][2], and have been widely utilized. Leveraging their maneuverability, flexibility, stealthiness, and low cost, UAVs can execute various combat missions on the modern battlefield, including intelligence gathering, surveillance, reconnaissance, precise strikes, and information relay [3]. However, traditional UAVs, due to their aerodynamic configuration, have structural shapes that are inconvenient for mass transportation and exhibit long launch preparation times, thereby impeding their mass and rapid deployment on rapidly changing battlefields. Consequently, catapult-launched folding UAVs have emerged.

The emergence of catapult-launched folding UAVs aims primarily to address the issues of space and time consumption during transportation and launch processes encountered by traditional UAVs. This paper firstly introduces the research status of catapult-launched folding UAVs in various countries, and focuses on key technologies including folding technologies for UAV wings and arms, mechanical or chemical catapult launch technologies, and post-launch stabilization control technologies. Finally, the paper provides an outlook on its application prospects and offers considerations for future development.

2. Current Development Status of Catapult-Launched Folding UAVs

The design concept of catapult-launched folding UAVs involves using mechanical or chemical energy as the launch power to rapidly deploy the folded UAV. This concept originated from a requirement proposed by the Defense Advanced Research Projects Agency (DARPA) of the United States in 1996 as a key technology [4].

Catapult-launched folding UAVs can be classified into two types based on their aerodynamic configuration: fixed-wing folding types and rotary-wing folding types. The following will outline the current development status of these two types of UAVs.

2.1 Fixed-Wing

The two institutions that initially responded to the technical requirements of the Defense Advanced Research Projects Agency (DARPA) were the Massachusetts Institute of Technology (MIT) and the Draper Laboratory. They utilized cannon-launched folding UAVs to achieve rapid response and wide-area reconnaissance. The conceptual model is depicted in Fig. 1 [4].

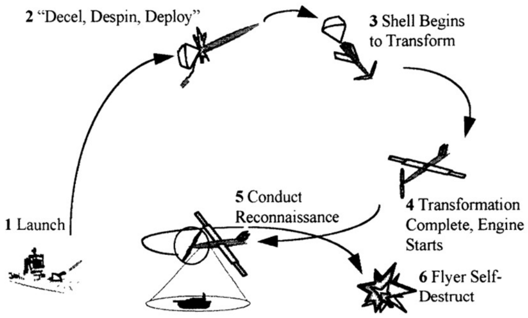

Fig. 1 Concept Model of Cannon-Launched Folding UAV

In 1997, researchers led by Hallam at the Massachusetts Institute of Technology (MIT), combining ballistics and aerodynamics, completed the system architecture and decelerator of WASP [5]. In 1998, Gavrilets et al. designed the control augmentation system for WASP [6]. Chiu and Shook, among others, analyzed and optimized flight trajectories and deployment sequences, and conducted flight tests [7] [8]. Trinh et al. developed a visual cueing aid to enhance reconnaissance and waypoint navigation performance [9]. In 1999, Jenkins investigated the application of composite materials in the wing system design of WASP [10].

Fig. 2 WASP multiplatform applications

In 2002, Martorana et al. from the Draper Laboratory confirmed the applicability of WASP on various launch platforms, as depicted in Fig. 2 [11]. In the same year, Kepets et al. from MIT investigated the roll control method of the WASP's twisted wing [12]. Radcliffe et al. studied the aerodynamic elasticity of WASP's multi-hinged wings [13]. In 2003, Obenchain et al. proposed a wing design using shape memory alloy, confirming the feasibility of roll control for twisted wings [14].

In 2002, Timothy et al. from ILC Dover, USA, developed a parachute for the QuickLook UAV to address stability issues after launch [15], where QuickLook is a fixed-wing UAV utilizing inflatable folding wings, as depicted in Fig. 3 (1). In 2004, Israel's Rafael company developed the Skylite UAV, which utilizes a launch tube to deploy electrically driven folding wings, as shown in Fig. 3 (2) [16]. In 2005, Russia publicly revealed the R-90 UAV, which features a tandem-wing design with folding wings, as illustrated in Fig. 3 (3) [17].

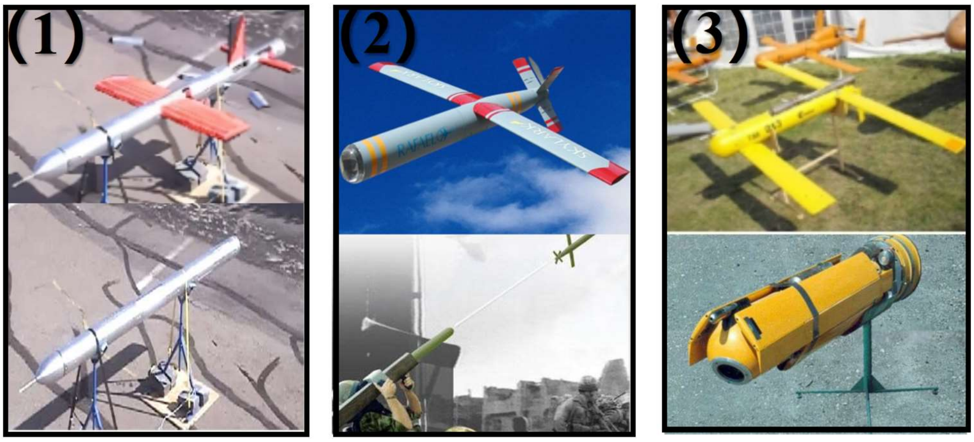

Fig. 3 UAV in reconnaissance

In 2004, the United States' Raytheon Company developed the Coyote loitering munition, a tandem-wing UAV with folding wings, as depicted in Fig. 4 (1) [18]. In 2009, AeroVironment, Inc., introduced the Switchblade series of loitering munitions, such as the Switchblade 300, as shown in Fig. 4 (2) [19]. In 2012, Israel's UVision company launched the HERO series of loitering munitions, including the HERO 30, as illustrated in Fig. 4 (3) [20].

In 2016, China Aerospace Science and Technology Corporation (CASC) introduced the FH-901 loitering munition, as depicted in Fig. 4 (4).

Fig. 4 loitering missile

With the development of catapult-launched fixed-wing folding UAVs, research tailored to different needs has emerged. In 2006, Proctor et al. from Cranfield University, UK, designed a tube-launched low-cost UAV, as shown in Fig. 5 (1) [21]. In 2014, Pake et al. from the University of Adelaide, Australia, proposed a folding UAV design that could be launched from a submarine, as depicted in

Fig. 5 (2) [22]. In 2015, Wang et al. from Harbin Institute of Technology, China, designed a lightweight catapult-launched folding UAV, as illustrated in Fig. 5 (3) [23]. In 2016, Bawa et al. from the University of Sydney, Australia, designed the BAT folding UAV, which utilizes low-cost PVC cylindrical storage for launch, as shown in Fig. 5 (4) [24]. In 2017, Lockheed Martin, UK, introduced the OUTRIDER, a disposable high aspect ratio folding-wing UAV launched from submarines, as depicted in Fig. 5 (5) [25]. In 2018, Ahmad Muzzamil et al. from Bandung Institute of Technology (ITB), Indonesia, adopted a tandem-wing structure for a tube-launched folding UAV, as shown in Fig. 5 (6) [26]. In 2021, Rockenbauer et al. from the Swiss Federal Institute of Technology in Zurich (ETH Zurich) developed the Dipper, a cross-medium UAV with motor-driven folding wings, as depicted in Fig. 5 (7) [27]. In 2023, Watson et al. from the Queensland University of Technology, Australia, developed a rocket-launched low-cost folding UAV, as shown in Fig. 5 (8) [28]. Chang Min et al. from Northwestern Polytechnical University, China, designed a vertical tube-launched folding-wing UAV called the Youjun, and proposed a secondary folding wing design based on dihedral angle constraints, as illustrated in Fig. 5 (9) [29].

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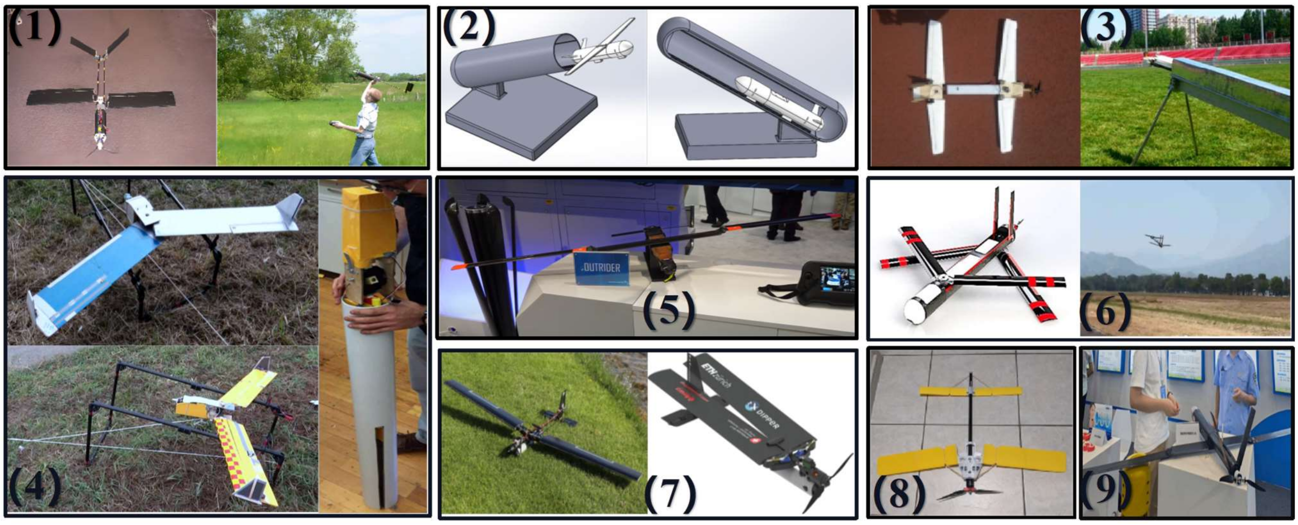

Fig. 5 Domestic and international research

2.2 Rotary-Wing

The single-axis rotary-wing folding UAV was initially researched, and in 2008, Gnemmi et al. from the Franco-German Research Institute of Saint-Louis proposed the concept of cannon-launched micro aerial vehicles [30], with the launch and deployment process depicted in Fig. 6 (1). In 2009, Gnemmi and Changey et al. completed the aerodynamic modeling of the single-axis rotary-wing folding UAV, named GLMAV 1.0 (Gun Launched Micro Air Vehicle) [31]. In 2012, aerodynamic performance estimation was completed [32], followed by aerodynamic performance numerical calculations for GLMAV 2.0 in 2014 [33], and the design of the ballistic launch flight control system in 2017 [34], along with the development of the visual system [35].

During this period, in 2010, Koehl et al. from the Nancy Research Center for Automatic Control in France conducted research on the aerodynamic model of GLMAV [36]. In 2012, Chauffaut et al. from the University of Technology of Compiègne in France investigated the transition from ballistic flight to autonomous attitude-stabilized flight [37], while Drouot et al. from the Nancy Research Center for Automatic Control in France studied the nonlinear trajectory tracking control law for GLMAV [38]. In 2013, Drouot et al. conducted a comparative analysis of linear and nonlinear control strategies for GLMAV [39]. In 2016, Roussel et al. explored a method for nonlinear modeling of GLMAV based on six-degree-of-freedom equations [40].

In 2017, Gnemmi et al. achieved the transition from theoretical model to prototype of GLMAV 2.0 [41], as shown in Fig. 6 (2).

In 2018, Tan et al. from Imperial College London proposed a design for a single-axis rotary-wing folding UAV named SkyEye, which can be launched from multiple grenade launchers [42].

In 2021, Denton et al. from Texas A&M University designed a single-axis rotary-wing folding UAV that can be launched from a 40mm grenade launcher, as depicted in Fig. 6 (3) [43].

In 2022, Yu Hualong et al. from Shenyang Aerospace University in China designed a catapult-launched coaxial dual-rotor UAV, as shown in Fig. 6 (4) [44].

Fig. 6 Single axis rotor catapult launched foldable drone

In 2017, Henderson et al. from the University of California proposed a design for a foldable, biomimetic structure hexacopter UAV that can be launched, as depicted in Fig. 7 (1) [46][47].

In 2018, during the ARLISS International Rocketry Competition, Foster et al. from Oklahoma State University designed a rocket-launched folding quadcopter UAV with a flipping arm, as shown in Fig. 7 (2)[48]. Lee et al. from the Korea National University of Transportation designed a folding quadcopter UAV with a flipping arm, as illustrated in Fig. 7 (3)[49].

In 2019, Pastor et al. from the California Institute of Technology developed a quadcopter UAV with catapult-launched folding capability named SQUID, as depicted in Fig. 7 (4) [50].

In 2020, Bouman et al. upgraded the SQUID to a foldable hexacopter UAV named SQUID 2.0, as shown in Fig. 7 (5) [51].

In 2019, DefendTex, an Australian company, developed the Drone 40, a suicide-type folding UAV launched via a 40mm grenade launcher, as shown in Fig. 7 (6) [52].

In 2020, Spear, an Israeli company, introduced the Ninox series UAVs and the VIPER series suicide UAVs. Among them, the Ninox 40 and VIPER are depicted in Fig. 7 (7) and (8) respectively [53].

In 2019, Tuna et al. from the Swiss Federal Institute of Technology in Zurich (ETH Zurich) designed the Folly, a quadcopter UAV capable of automatic deployment and folding unfolding, as shown in Fig. 7 (9) [54].

In 2022, Lyu T et al. from Beijing Institute of Technology in China designed a self-deploying spherical quadcopter UAV that can be ejected, as depicted in Fig. 7 (10) [55]. In the same year, d'Arcy et al. from Queensland University of Technology in Australia designed a rocket-launched folding quadcopter UAV, as illustrated in Fig. 7 (11) [56].

In 2023, Gökbel et al. from Trakya University in Turkey designed a foldable quadcopter UAV and launch device, as shown in Fig. 7 (12) [57]. You Anhua et al. from Nanjing University of Science and Technology in China proposed a cylindrical launch-based design for a miniature quadcopter UAV, as depicted in Fig. 7 (13) [58].

Yulin Bai et al. from Shanghai Jiao Tong University in China designed the Nezha-F, a cross-medium UAV capable of deployment and automatic folding unfolding, as shown in Fig. 7 (14) [59].

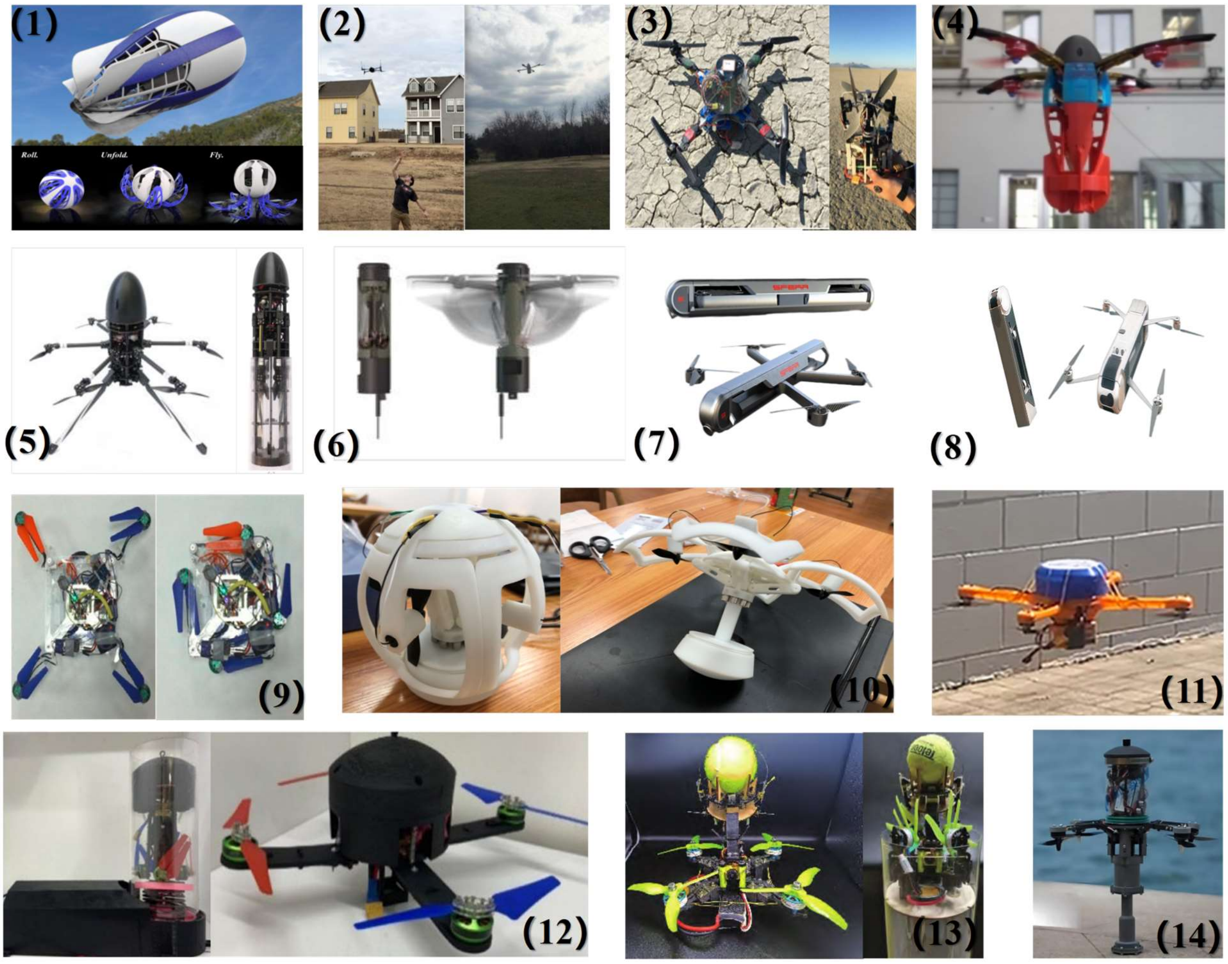

Fig. 7 multi-rotors catapult launched foldable drone

3. Key Technologies

The differences between catapult-launched folding drones and traditional drones primarily lie in folding technology, catapult launch technology, and stability augmentation control technology. This section will outline the relevant technologies applied in existing folding drone applications.

3.1 Folding Technology

Folding technology is one of the key technologies for catapult-launched folding drones. It involves achieving compact volume after folding while also enabling rapid deployment. The unfolding of folding wings or arms requires control over deployment time, speed, and angle. Folding wings or arms can be classified into inflatable, mechanical, and electrically driven types based on their folding mechanisms.

Inflatable folding wing deployment is powered by high-pressure air cylinders, as illustrated in Fig. 8 [15]. This method is primarily employed by drones such as the Quick Look UAV.

Fig. 8 inflatable

Mechanical folding wing or arm deployment utilizes sources such as torsion springs and centrifugal force. When driven mechanically, the deployment timing needs to match the spring force of the torsion spring, for instance. After deployment, mechanisms such as locking slots at the joints are employed to secure the structure, as depicted in Fig. 9. Examples of applications include folding wings, folding propellers, and folding arms, as shown in Figs 9(1) [28], (2) [44], and (3) [48], respectively.

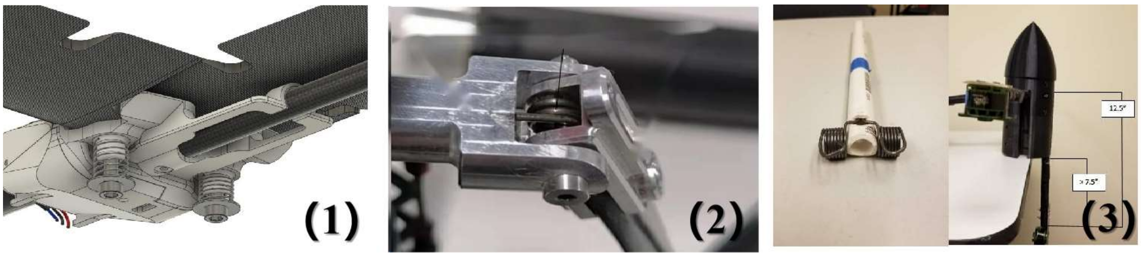

Fig. 9 Mechanical drive mechanism

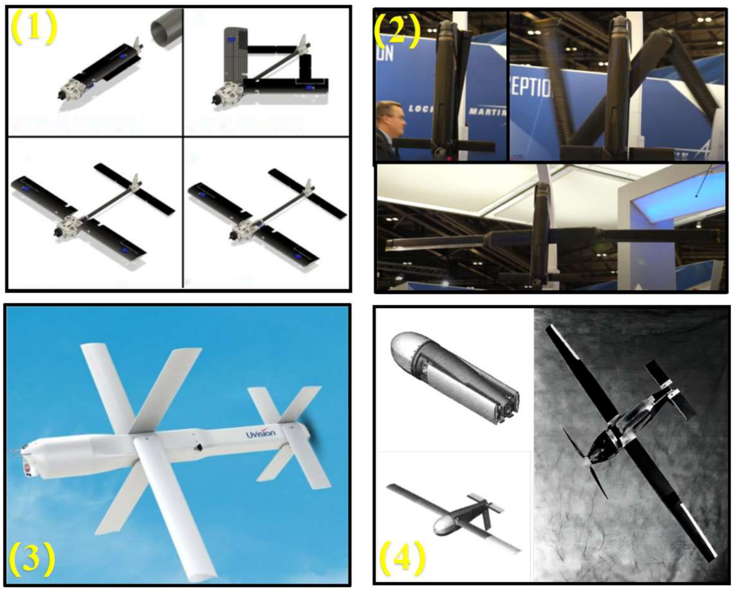

Fig. 10 Mechanical folding wing

Mechanical folding is widely utilized in catapult-launched folding drones and can be further classified based on the folding method of the drone. Among the existing mechanically-driven folding wing drones, R-90, Skylite, Coyote, Switchblade, and FH-901 utilize V-shaped rotating wings, as depicted in Fig. 10(1). OUTRIDER and Yousun adopt a straight rotating secondary folding wing design, as shown in Fig. 10(2). HERO 30 and HERO 90 feature cross-shaped rotating wings, illustrated in Fig. 10(3). WASP utilizes a multi-segment folding wing design, as seen in Fig. 10(4).

Mechanically-driven folding arm drones from the National Institute of Technology, Jinwoo University, China, employ an upward folding arm design for quadcopters, as depicted in Fig. 11(1). SQUID, SQUID 2.0, rocket-launched quadcopters from Oklahoma State University, Drone 40, and the spherical drone from Beijing Institute of Technology utilize downward folding arm designs, as shown in Fig. 11(2). Drone 40 and VIPER adopt inward folding arm designs within the plane, as illustrated in Figs 7(7) and (8).

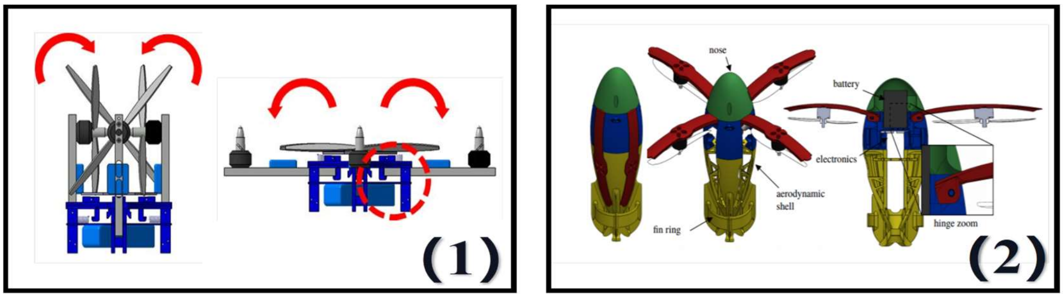

Fig. 11 Mechanical folding machine arm

The mechanically-driven folding propeller drones utilizing centrifugal force as the power source for deployment include GLMAV 2.0. On the other hand, drones like the catapult-launched coaxial dual-rotor drone from Shenyang Aerospace University employ torsion springs to drive the folding propeller blade deployment.

Electrically-driven folding wing and arm drones utilize servo motors as the power source, relying on sensor data and controller commands to achieve controlled deployment of the arms and wings. Dipper employs electrically-driven V-shaped rotating wings, as depicted in Fig. 12(1). Folly utilizes an inward folding electrically-driven folding deployment method, as shown in Fig. 12(2). Nezha-F adopts downward folding electrically-driven arms, as illustrated in Fig. 12(3).

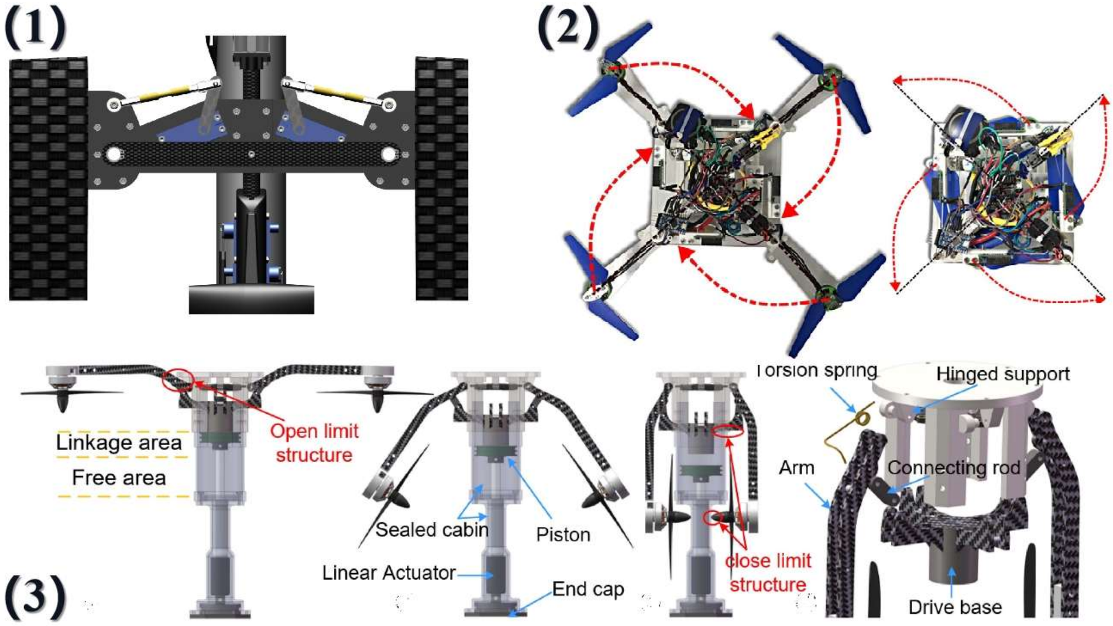

Fig. 12 Motor driven

3.2 Catapult Launch Technology

After folding the wings or arms, drones typically assume a cylindrical structure, facilitating placement within a launch tube. Various power sources such as rocket-powered, pneumatic, cannon-fired, and spring-loaded mechanisms are used to achieve the catapult launch of unfolded drones.

Rocket-powered launch involves using small-scale launch rockets to quickly propel the folded drones into the air. Upon reaching a specified altitude, a signal within the rocket triggers the release of the folded drone. Additionally, a disposable parachute mechanism is often equipped on the folded drone to provide cushioning for stable control after launch. Drones launched in this manner include the folding quadcopter from the National Institute of Technology, Ulsan, South Korea, as depicted in Fig. 13. Similarly, folding fixed-wing drones from Queensland University of Technology and folding quadcopter drones from Oklahoma State University, USA, are launched using rocket-powered methods.

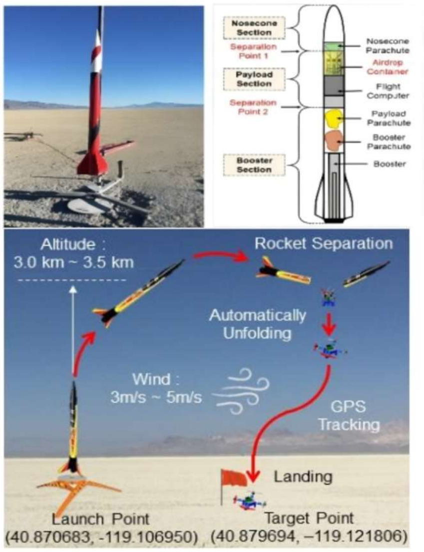

Fig. 13 Rocket assisted propulsion

The use of cannon-powered launch for folded drones is currently the mainstream launch method. This launch method combines ammunition launch technology with the expansion of gas from burning gunpowder to propel a piston for launching folded drones. The cannon launch mechanism of the Israeli VIPER is depicted in Fig. 14. Additionally, other folded drones such as WASP, QuickLook, Skylite, R-90, Coyote, Switchblade, FH-901, Drone 40, and GLMAV also utilize this method.

Fig. 14 Gun-launched

The design principle of pneumatic catapult launch is similar to that of cannon launch, with the difference being the use of encapsulated high-pressure gas instead of the high pressure generated by burning gunpowder. Drones launched using this method include SQUID, SQUID 2.0, and the single-axis rotary-wing folding drone from Shenyang Aerospace University. In the case of SQUID 2.0, the launch mechanism incorporates the design concept of a T-shirt cannon air gun. The required gas-to-drone weight ratio for launch is calculated based on the weight of the drone, ensuring that the launch acceleration is controlled at 50g for stable deployment. The launch process is depicted in Fig. 15.

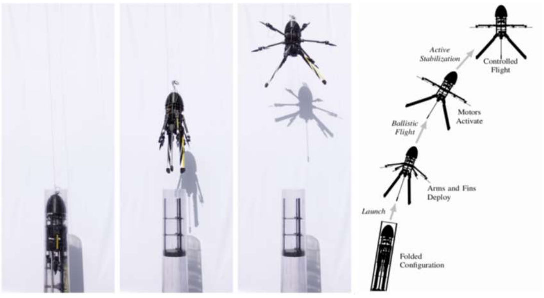

Fig. 15 Pneumatic catapult

Elastic launch primarily utilizes the elastic potential energy of a spring to convert into kinetic energy, propelling the drone upon release. The launch mechanism, as shown in Fig. 16, is the spring launcher of the folding quadcopter from Trakya University, Turkey. BAT and the fixed-wing catapult-launched folding drone from Harbin Institute of Technology also utilize elastic launch.

Fig. 16 Elastic ejection

3.3 Stabilization and Control Techniques

After launching from the launch tube, the catapult-launched folding drones need to deploy their wings or arms in the air and achieve stable attitude and position control while in motion.

Fixed-wing aircraft adjust their flight attitude in real-time using elevators and ailerons for pitch, roll, and yaw control. WASP utilizes a proportional-derivative (PD) algorithm-based stabilization controller, which corrects angular velocity and angular acceleration by using feedback from yaw rate error and roll rate to improve its wind resistance stability. Dipper features a four-bar linkage structure with electrically driven folding wings, which automatically fold based on sensed pressure values to reduce water resistance during aquatic travel. It employs a cascaded PID control algorithm to achieve posture control during both aerial flight and underwater gliding.

Single-axis rotor UAVs achieve roll and pitch movements by controlling rotor speed and servo angle. The catapult-launched single-axis rotor folding UAV from Shenyang Aerospace University adopts a PID-robust hybrid control method. It controls the inner loop attitude through a robust control algorithm using the S/T hybrid sensitivity design method and mitigates the interference of trajectory flight uncertainty on the attitude loop. The single-axis rotor folding UAV from Texas A&M University employs manual throttle signals to control the attitude correction trigger timing. It utilizes cascaded PID control for pitch and roll and single-level PID feedback control for yaw[61].

Multi-rotor UAVs achieve ascent, descent, roll, pitch, and yaw movements by adjusting the speed of each rotor. The rocket-launched folding quadcopter from Oklahoma State University utilizes a speed data fusion detection method and cascaded PID attitude control algorithm. It uses velocity and Z-velocity numerical detection to determine if the UAV has reached its peak, triggering attitude correction and achieving stability control from launch to stable hover in the deployed state. The rocket-launched folding quadcopter from the National University of Ulsan in South Korea employs a cascaded PID algorithm with an enhanced altitude planner for UAV attitude and position control, enabling the UAV to fly on a slope after launch, significantly reducing its flight distance[62]. The SQUID UAV ignites nichrome alloy burning wires through relay switches controlled by manual remote control to control the timing of arm deployment. SQUID 2.0 adopts a Kupman-based Model Predictive Control (MPC) method to achieve attitude stability control during the launch phase[62][63]. Folly utilizes a PID attitude control method and electrically-driven crank rocker-type planar folding arms with linear deployment characteristics, allowing speed and timing of arm deployment to be controlled through motor speed. The spherical UAV from Beijing Institute of Technology adopts a cascaded PID attitude control method and electromagnetic self-locking parachute folding deployment control method, where the launch phase controls arm deployment timing by detecting acceleration or remote control commands. The parachute deployment method mitigates instantaneous arm deployment shocks, reducing attitude changes during arm deployment. Nezha-F employs a piston-type buoyancy adjustment system for foldable arms, automatically folding and unfolding based on UAV environmental conditions, and utilizes a dual closed-loop PID control method to achieve both water and air missions.

4. Conclusion

The article first introduces the development process of foldable-wing fixed-wing drones and foldable-arm rotary-wing drones that can be launched from launch tubes, and outlines key technologies for such drones, including folding technology, catapult launch technology, and stabilization control technology.

In future development, catapult-launched foldable drones will move towards intelligence and clustering, striving for fully autonomous launch and recovery to improve deployment and operational efficiency.

In future applications, catapult-launched foldable drones will be more suitable for individual, vehicle-mounted, and shipboard carrying in military applications, and can be quickly deployed while on the move. In civilian applications, they can be used for vehicle rescue, urban patrol, and other tasks, as well as for integrated air-to-ground reconnaissance missions.

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