

# Design of a Catapulted Self-deployable UAV

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**Abstract.** Unmanned Aerial Vehicle (UAV) is playing a gradually enhanced role in fields of recon and information acquisition, however restricted departure condition of fixed wing aircrafts, take-off preparation time of multirotor aircrafts etc. have limited its further applications. This research aims to combine advantage of hovering and self-deployable departure to reconcile the shortcomings, meanwhile adapts to drone swarm trend. A catapulted self-deployable quadrotor is designed using 3D modelling software, and later a compatible self-deployable control algorithm is developed using STM32F103 microcontroller, along with its circuitry. Eventually, a prototype of the design is 3D printed, assembled and tested. This design shows merits of easy to carry, low requirements for take-off conditions and good hovering performance and is compatible for multi-UAVs cooperation tendency.

## 1. Introduction

Unmanned Aerial Vehicle (UAV) involves in various types of works, such as emergency rescue and nocturnal rescue [1], surveillance of target [2], detection of threat target around oil Pipeline [3], Cruise missiles [6] etc. Along with the development of the UAV mechanical structural design and intelligence control algorithms, implementation of UAV has been greatly bolstered. According to structural discrepancy, current UAVs can be classified into: fixed wing aircrafts, multi-rotor drones, ornithopter etc.

Fixed wing aircrafts and multi-rotor drones are two types of most commonly used UAVs in information acquisition and target surveillance. This is due to multi-rotor drones having merits of being able to take off and land vertically without runway and hover. Multi-rotor drones have high practicability, strong flexibility and good stability, and are convenient for fine operation, meanwhile simple to operate [1]; fixed wing aircrafts advance in rapid target approaching time and ability to be catapulted.

Nevertheless, when facing crucial scenarios such as public emergency, combat conditions, crowded and cramped space, both fixed wing aircrafts and multi-rotor drones would find themselves difficult to take-off [5]. Fixed wing aircrafts require take-off runway which greatly limits the departure condition, while multi-rotor drones require unhindered vertical area. Not to mention that multi-rotors' long

piloting time to reach the target after departure. Accordingly, flex-wing vehicle design might loosen the restricted departure condition.

Although flex-wing aircrafts have long been developed, none of the existing design can meet the demand. Figure 1 displays “Airborne radar target” aircraft, which was designed by U.S. Naval Research Laboratory [7]. But the intrinsic merits of fixed wing aircraft confined this drone not able to hover at a position and conduct fine operation or fixed-point surveillance. Yet the relatively large volume consumption also reduced its portability. Reference [8-9] have introduced folding UAVs, however, the deploying procedure still requires manual operations, furthermore, approaching of target position requires manual navigation. Also multi-UAVs cooperation begins to burgeon, this tendency requires UAVs to reduce size and be able to achieve multi-UAVs release.

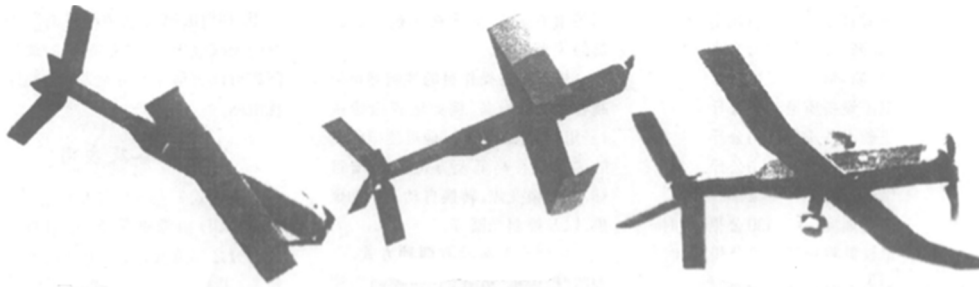


Figure 1. “Airborne radar target” aircraft

Thence, this research proposes a catapulted self-deployable quadrotor to acquire merits of easy portability, low requirements for take-off conditions and good hovering performance and to adapt to drone swarm trend. Section 2 will introduce the general design of the quadrotor; Section 3 will focus on mechanical design; section 4 will explain control algorithms and circuitry design; section 5 will demonstrate the testing of the prototype, finally a conclusion is attached in the end.

## 2. General design

The gist of this design is to achieve a catapulted self-deployable quadrotor with minimum size. To meet the requirements, we have conceived a rough conception. The quadrotor has a four-rotor mechanism which can be automatically deployed instantly by triggering mechanism. When the rotor is deployed, a closed-loop control can be accomplished by the sensors on the aircraft to adjust to face-up position and hover.

The aircraft adopts the overall spherical design after folding. The quadrotor rotors are symmetrically distributed around the sphere, which becomes a part of the sphere after contraction. The lower part of the sphere is provided with a cavity, which is the space for placing the power supply and circuit and other elements.

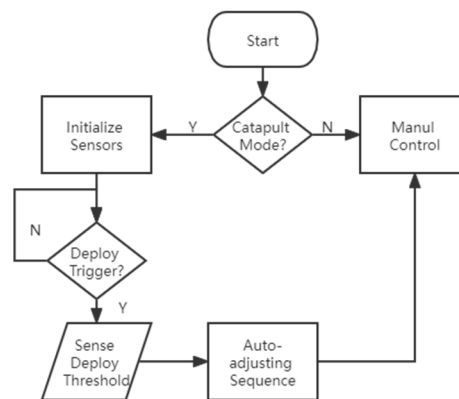


Figure 2. Control Sequence Scheme

Figure 2 shows a flow chart for the control sequence of the aircraft. After starting the flight mission, the operator can select whether this flight will be catapulted to take-off or departure from ground base. If the ground-level takeoff mode is selected, the aircraft can be placed horizontally, and then the quadrotor can be unlocked for manual operation. If the catapulted mode is selected, the trigger command can be sent when the UAV reaches the predetermined after the aircraft is catapulted. During which, the aircraft can detect the conditions suitable of rotor deployment, that is, when the aircraft is in face-up posture, the rotor can be deployed. Then, the aircraft will enter the autonomous hovering closed-loop control to realize the instantaneous re-horizontal adjustment of the aircraft fuselage attitude. The aircraft will then hover and enter a locked state, at which point the operator can unlock and operate the aircraft manually.

For purpose of realizing the design, pertinent methods are implemented. We have used Autodesk Inventor, a 3D modelling CAD for mechanical designing, stress analysis, visualization and simulation. As for microcontroller (MCU) selection, STM32F103 is selected for its powerful computation ability, low power consumption [11] and low cost. Circuit design is implemented on Altium Designer, circuit design software.

### 3. Mechanical design

The rotors of the UAV are symmetrically distributed in four directions: the front and back, left and right of the body. The four rotors are in the same height plane. The four motors are symmetrically installed on the bracket end of the aircraft, and other electronic components are installed in the middle gap.

One of the highlights of the UAV can be realized is that the operator can launch the quadrotor autonomously after throwing it out and hover in mid-air to enter the working state. The mechanical part consists of a total of 40 parts of the expansion structure, self-locking, opening structure, circuit control installation part. It has the characteristics of small size, easy to carry, less requirements for takeoff conditions, reliable expansion and self-locking structure.

Compared with traditional UAVs, we designed a nearly spherical shell, which is small in volume and convenient to carry. And the round shell has strong extrusion resistance, protecting the transportation process of the UAV is not easy to be damaged. The casing is hollowed-out, providing plenty of room for airflow while protecting the rotors from impact. Figure 3 and Figure 4 separately shows the contrasted and the deployed state of the UAV.

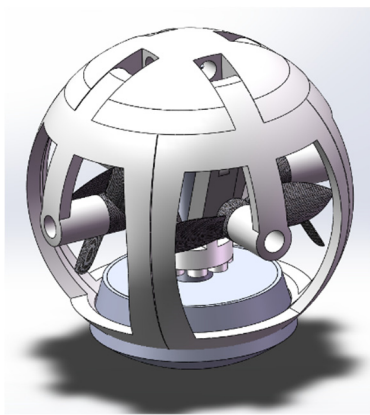


Figure 3. Contrasted state of the UAV model

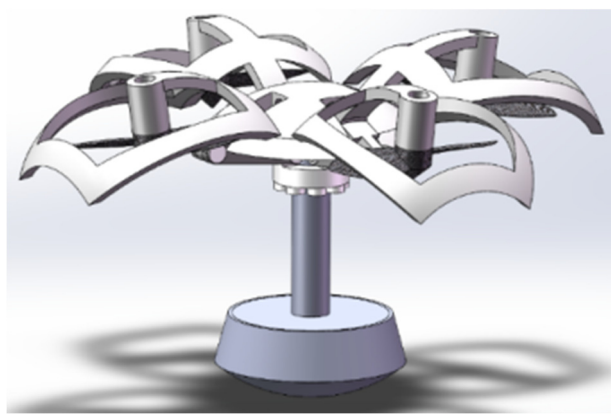


Figure 4. Deployed state of the UAV model

In order to realize the short time deployment of rotors, a folding method of umbrella-shaped shrinkage structure design is introduced. When using this folding method, because the rotors move in opposite directions, the impact loads caused by the rapid expansion of the rotors cancel each other, and the torsional moment acting on the fuselage is relatively small, which is very helpful to maintain the stability of the aircraft in the air attitude. At the same time, the rotors are locked before deployment to

reduce unnecessary vibration. In addition, the pairwise lock release also helps to ensure the synchronization of rotors deployment. In this design, we use the electromagnet and reset spring combined mechanism, so that it can keep the original locking performance at the same time, but also can be reused, and ensure the safety of use.

For instance, Figure 5 shows the deployed supporting structure of the drone. In the deployed mode, the supporting mechanism selects the slider connecting rod mechanism, and determines the appropriate length of the connecting rod through several iterations to ensure the larger blade expansion Angle and pressure Angle, so that the expansion process is smooth and reliable.

Due to the large weight of the motor, in order to reduce the influence of external environment and dead weight on the wing during flight, the pressure Angle is close to  $90^\circ$  to achieve the self-locking condition after fully unfolded, ensuring that the wing will not oscillate up and down during flight.

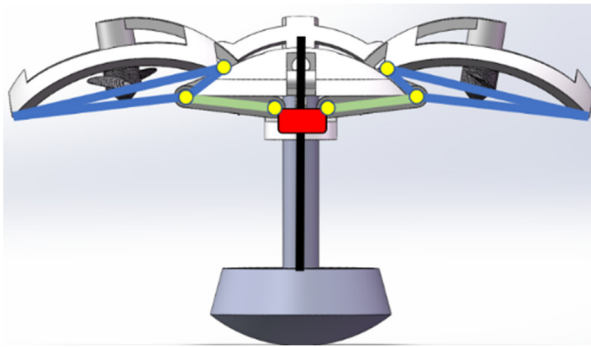


Figure 5. Deployed supporting structure

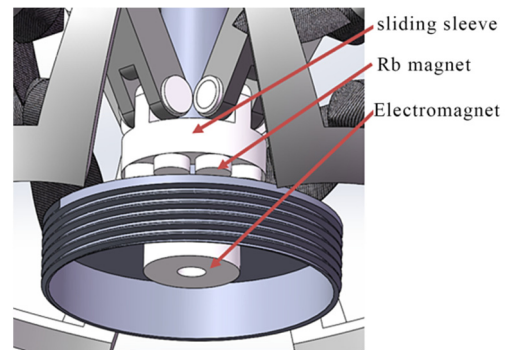


Figure 6. self-locking structure

When the sensor detects that the expansion condition is reached, the electromagnet is energized to make the upper and lower magnetic poles face to face, generating instantaneous repulsive force to remove the self-lock, and relying on the installed spring structure to expand the UAV rotor. Figure 6 displays the mentioned self-locking structure. This structure avoids the wear and damage caused by the mechanical self-locking structure with the increase of use times, and improves the self-locking stability and the reliability of spring.

#### 4. Control algorithms and circuitry design

The control system of this catapulted self-deployable quadrotor involves control algorithm coding and compatible circuitry design. In the circuitry design part, excluding the common quadrotor piloting circuit integration, sensor selection and mechanical boundary of the printed circuit board (PCB) definition are key obstacles. As for algorithm design, the self-adjusting re-horizontal hovering sequence is the preponderant difficulty, which is also a key innovative point in this research.

In following subsections, both control algorithms and circuitry design procedures are listed in detail.

##### 4.1. Circuitry design and hardware selection

We have selected STM32F103C8T6 as the main MCU of the quadrotor. The MCU will undertake the most data processing responsibility. In order to bridge communication between the drone and remote controller, a 2.4G communication module, which we used NRF24L01 in this study, is integrated. To sustain further manual control of the UAV, MPU6050 module is embedded, which is a commercial gyroscope module. A power management circuit is designed with ability to stabilize the supply of 5V input voltage. A series of pin headers are also included so that sensors that used to achieve self-adjusting re-horizontal hovering sequence can be attached. The schematic diagram of the circuit containing modules mentioned before is shown in Figure 7. By using Altium Designer software, we are able to schedule the PCB of the circuitry, which further delivered to customized fabrication.

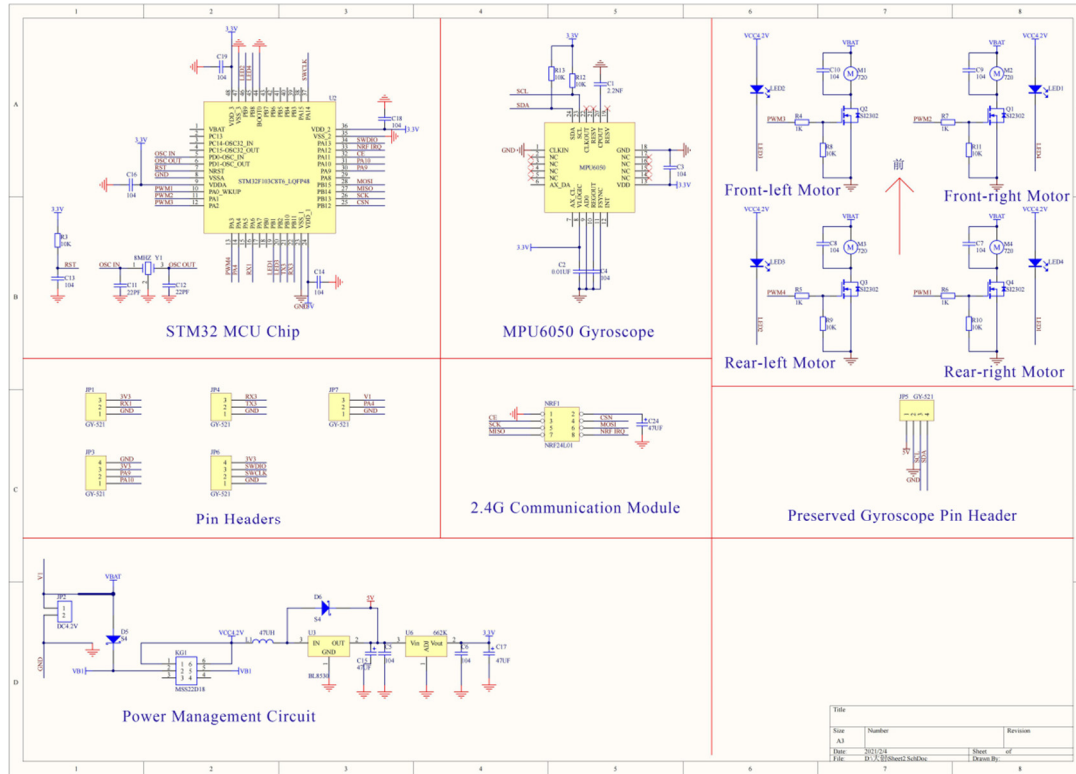


Figure 7. Schematic Diagram of the Circuit

A tilt sensor and inclinometer are selected for detecting the threshold of the self-adjusting re-horizontal hovering sequence.

Tilt sensor has merit of being a one-hot coding sensor, which means it only recall two states of values, indicating whether the sensor is tilted. This property is valuable to our design, that we can deposit the tilt sensor in a vertically face-up position. If under condition that manually deploy trigger command is received, the tilt sensor could detect fuselage orientation and feedback the trigger signal for unfolding the rotors.

HWT31 is a inclinometer that promised to function properly even under sharp vibration [12]. As our departure method touch on catapulting, vibration and rapid rotation are inevitable; HWT31 is suitable for such working conditions. It recalls angular information around two perpendicular axes, which when the module is horizontally placed on the drone, it will feedback the information of the angle between fuselage and the horizontal ground. This module is used to feed sampled values to the close-loop control algorithm of the self-adjusting re-horizontal hovering sequence.

The study chose to use polymer batteries with a stable voltage of 3.7-4.2V, which is suitable for small UAVs and lasts about 5-10 minutes. Meanwhile the electromagnet part is customized by the manufacturer. The parameters are 6mm inner diameter, 20mm outer diameter, 3V driving voltage and less than 10mm thickness, which is more in line with our mechanical design requirements.

#### 4.2. Control algorithms developing

As Figure 8 shows, when the system begins, UAV system will enter the initialization phase, this phase consists of enabling the system clock, Nested Vectored Interrupt Controller (NVIC) system initialization, IIC communication function initialization, PID parameters initialization, LED related pin initialization, PC communication pin initialization, HWT31 module and the corresponding pin initialization, four-channel motor Pulse width modulation (PWM) initialization, NRF24L01 module initialization, timer 3 interrupt initialization, etc.

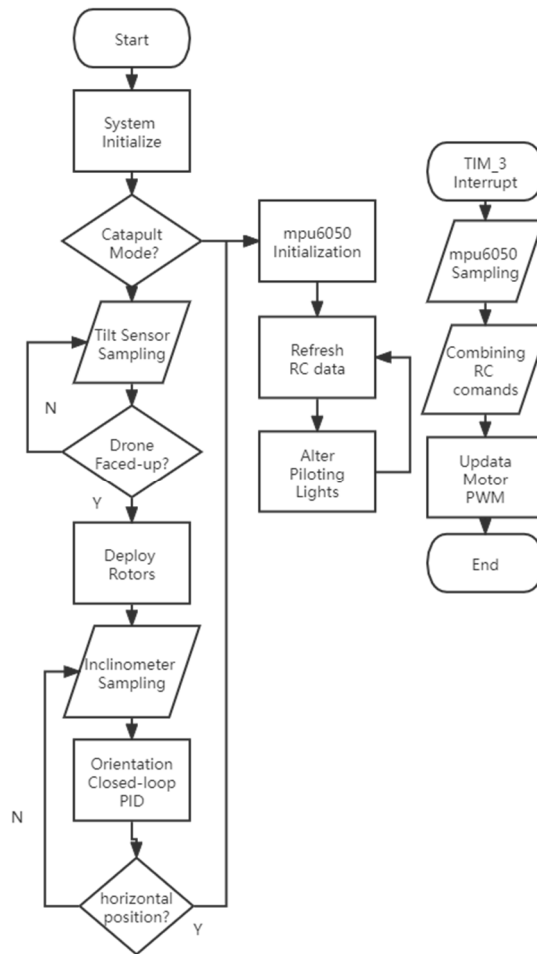


Figure 8. Flow Chart of Control Sequence

After that, the UAV enters the state of waiting for receiving mode selection instruction. At this moment, the operator can select the departure mode by using the remote control, which will be transmitted to the aircraft through NRF24L01. If the ground base takeoff mode is selected, the UAV initializes the MPU6050 and deploys the rotors. After that, the UAV enters the locked state and waits for the operator to unlock manual control. If the catapult mode is selected, the aircraft enters the state that is, waiting for the rotors deploying command.

At this point, the operator can throw the aircraft into the air, or use other air drop methods to make the UAV airborne. This study considers that the design of fully autonomous deployment of the rotor is deficient by canceling the sending of the rotor deployment command. That is to say, if the rotor is fully autonomous deployment, even if the accelerometer is used to judge that the acceleration is zero, that is, the highest point is the deployment point, or directly using the front to the air is the deployment judgment point, it is not appropriate. The drone could have misjudged the aircraft to have reached its maximum altitude when the operator's arm was thrown upward and improperly extended the wing, causing injuries. Therefore, this study still added the function of manually selecting the deploying position, namely the time to unfold the rotors, and the autonomous rotor deployment process can be interpreted as the aircraft can find the appropriate point to deploy the rotors even in the rotation state, avoid somersault or unnecessary large attitude adjustment, and automatically deploy the rotors and hover.

Therefore, when the aircraft receives the rotor deployment command at any Angle in the air, it enters the self-judgment of deployment time. There are many reasons for the choice of HWT31 module: 1. MPU6050 requires a long time to initialize, compared with the core unit SCA60 used by HWT31 module, which has a short time to initialize, and can be used to fly away under emergency conditions to a large extent. 2. MPU6050 has more crucial criterion for initialization Angle. In the absence of electronic compass calibration, the Angle information obtained purely by Inertial Measurement Unit (IMU) attitude solution is often biased. 3. Intuitive 2D inclination data also makes attitude adjustment easier by HWT31, that is, euler Angle attitude calculation is not needed, making PID closed-loop code more intuitive, etc.

When the drone receives the rotor deployment command signal, the plane get HWT31 module data to determine the plane fuselage roughly faced up, launched rotor, through research, using MPU6050 module realization of the goal of space Angle is greater than 80 degrees Angle adjustment, PID convergence efficiency is low, to achieve the rapid deployment of the aircraft rotors, in response to emergency situations, This study designed to deploy the rotors when the plane fuselage faced up. The electromagnet module is then triggered to deploy the rotors.

After the rotors are deployed, PID control is carried out based on the two-axis inclination angle information returned by HWT31. When the expected horizontal target is reached, the aircraft initializes the MPU6050 module, which makes the initialization condition of MPU6050 level, thus increasing the accuracy of IMU attitude solution. Then start timer 3 interrupt, and the aircraft enters the normal operational state.

Then the UAV will hover at a constant speed and enter the locked state. The operator unlocks and manually controls the aircraft. The main program enters the main loop, and the main loop updates two things, namely, updates the flight status light, and updates the aircraft attitude information and stores it in the register to be sent to the PC.

In timer interrupt 3, it is realized to trigger interrupt once in 3ms. In interrupt, MPU data update, remote control data update, PID attitude adjustment based on attitude Angle data are carried out, and then PWM is adjusted. Every 6ms, the attitude Angle of the MPU data obtained was calculated.

## 5. Results

The prototype of the quadrotor is 3D printed with certain items customized. The PCB is fabricated and integrated with Surface Mounted Technology (SMT). The parts are finally assembled with Figure 9 showing the pictures of the prototype.



Figure 9. Prototype of the Catapulted Self-deployable Quadrotor

Figure 9(a) shows the contrasted state of the UAV;

Figure 9(b) shows the deployed state of the UAV



The quadrotor is manually thrown tested. With successfully deployed automatically, the aircraft showed a stability maneuvering at near ground altitude for piloting time of 3 mins. The cavity preserved still has space for further implantation of surveillance modules.

Moreover, due to optimal departure requirements and reduced size, the catapulted self-deployable quadrotor shows a prospect of being able for multi-UAVs cooperation.

## 6. Conclusion

A catapulted self-deployable UAV is designed in this study. Mechanical design with the four rotors capable of being expanded and contracted instantaneously by using a symmetrically distributed driving mechanism of connecting rod - slider like umbrella mechanism is adopted. The design mechanism is exquisite and has high robustness, convenient disassembly and maintenance. A self-adjusting re-horizontal hovering sequence closed-loop control system is developed, with innovatively using tilt sensor and inclinometer.

Our design has merits of optimal take-off condition requirements and minimal volume consumption. This enables the catapulted self-deployable UAV adequate for proceeding tasks in fields for instance, public emergency, combat conditions, and crowded and cramped space surveillance.

Although multi-UAV cooperation is not completed in this study, the remaining cavity on the aircraft is demonstrating a promising prospect of developing towards the drone swarm tendency.

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