Review

Ballooncopter – A new prospective type of UAV

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ABSTRACT

It has been shown that an increasing demand for cheap and useful UAVs in recent years. At the same time, the requirement to reduce emissions (applying "green" technology) is also an increasingly urgent. The paper introduces a ballooncopter which combines the advantages of multi-rotor aircraft (drone) and balloon to meet the above requirements, and proposes solutions to overcome mechanical problems arising when coupling the balloon body and drone, citing examples of forest protection and some other application possibilities.

Keywords: Flight vehicle; Drone; Balloon; Remote monitoring; Helicopter.

1. INTRODUCTION

Recently, the Vietnam Intellectual Property Agency has decided to provide a patent for a useful solution for a "lighter-than-air Helicopter" [6]. This flight vehicle is also called a ballooncopter (BH), a smart combination of a balloon and a drone (multi-rotor aircraft). Figure 1 shows an example of a BH (the retractable landing gear system is not shown here).

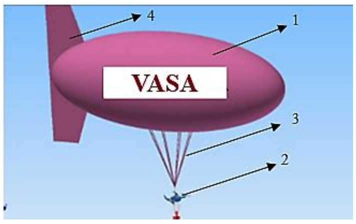

Figure 1. *Example of a BH used for forest protection observation BVR-100:*
Main parts: 1 - Balloon body; 2 - Drone with camera+transmission system; 3 - Joint assembly with ball joints and soft suspension wire (figure 7); 4 - Vertical tail.

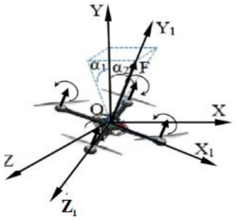

Figure 2. *Formation of the thrust vector* $\vec{F}$.

As is known, multi-rotor unmanned aerial vehicles (commonly known as drones) have been developed and widely used in recent decades for aerial photography and filming (flycam), in agriculture, and in national defense and security. This is because they are easy to manufacture (cheap) and easy to control. Drones often use GPS so they have an intelligent control system, making it easy to control all 3 angular coordinates (pitch angle, tilt angle, and direction angle) and 3 longitudinal coordinates of the center of mass (altitude, longitude, and latitude).

Drones create thrust by rotating the propellers, increasing and decreasing thrust by increasing and decreasing the rotation speed, overcoming the reaction torque by arranging pairs of rotors rotating in opposite directions, instead of using tail rotors like on conventional helicopters. The pairs of rotors rotating in opposite directions also simultaneously eliminate the precession torque caused by the gyroscopic effect. The rotors are installed with rotation axes perpendicular to the same reference plane. Although the pairs of propellers rotate in opposite directions, due to the opposite rotation, they create parallel force vectors in the same direction, synthesizing into the thrust vector $\vec{F}$ of the entire drone in the direction perpendicular to the reference plane of the drone (figure 2).

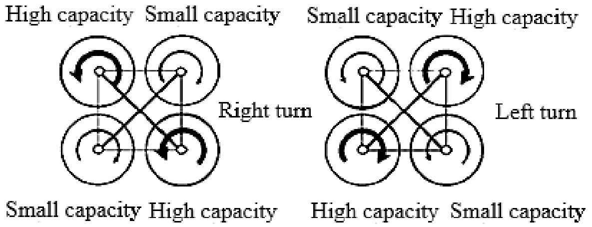

Figure 3. *Directional control in the horizontal plane.*

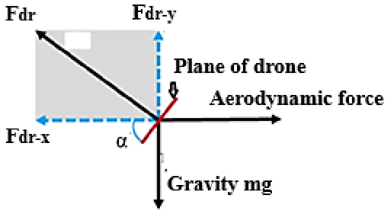

Figure 4. *Force vector* $\vec{F}$ *decomposed into 2 components.*

If the rotations of the rotors are equal, the reference plane and the $\vec{F}$ vector remains the same, keeping the angles α_1 and α_2 constant. If we want to change the angle, for example, angle α_2, we need to change the rotational speed and thrust of the corresponding rotor pair. If we want to change the direction (yaw angle) of the thrust vector relative to the ground, we need to increase or decrease the power of the corresponding rotor pairs, causing an imbalance in the reaction torques (figure 3).

When controlling flight using thrust vectors, it is necessary to control the magnitude (modulus), the angles α_1, α_2 and the angle of direction relative to the ground of the force vector $\vec{F}_{dr}$, for example, to fly level (constant altitude), it is necessary to create a force component F_{dr-y} that balances gravity, to counteract aerodynamic forces (caused by the movement of the aircraft and/or by wind), it is necessary to create force F_{dr-x} and/or F_{dr-z} to balance the aerodynamic forces (figure 4).

Thus, an intelligent control system (figure 5) is needed, including a microcontroller (7) with embedded software (8) installed to issue appropriate commands to the executive block (9), increasing and decreasing the rotation speed of the rotors 2 on the drone to control the thrust vector (magnitude and angles of the vector - figure 4). The input signal of the microcontroller will be the signal of the sensors (4, 5, 6): motion sensor (inertial sensor - IMU), position sensor, speed, flight direction - GPS/GNSS, flight altitude sensor and receiver (10), wireless control commands from the remote control device (11).

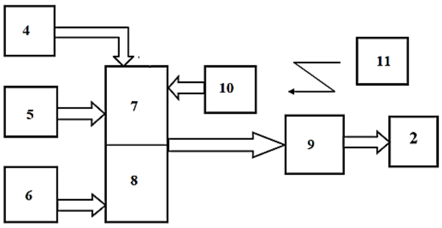

Figure 5. *Block diagram of the flight control system of a drone.*

Figure 6. *Some types of balloons and airships.*

These flight vehicles have very high stability in both angular and linear spatial coordinate position in windless/windy conditions, and the ability to take off and land vertically. However, the basic disadvantage of drones is that they cannot carry heavy loads and cannot fly for long time (in terms of aerodynamics, a rotor (rotating blade) like a classic helicopter is optimal, however, the option of ≥ 4 rotors with rotating blades easier to manufacture and control, so it is still strongly developed for the purpose of only needing to carry light loads and fly for a few dozen minutes.

Lighter-than-air vehicles, due to Archimed’s buoyancy, do not require energy to maintain lift, which can help us overcome the above disadvantages of drones. Lighter-than-air vehicles are usually filled with light gases (helium, hot air, and hydrogen, which is rarely used because it is flammable and explosive). Currently, there are 2 types of lighter-than-air vehicles (figure 6).

We can build an airship that combines a drone with a balloon body (two available technologies) to fly for a long time/carry heavy loads while still maintaining the advantages of an independent drone (easy to control and easy to manufacture). To increase flight time or total weight without making the size too large, we can pair the drone with the balloon, this combination needs to maintain the above advantages of the drone.

This article will analyze the problems arising in the above combination process, propose solutions in terms of mechanics and mechanical engineering, and give an application example to illustrate. Readers who are interested in the control system of ballooncopters, please see another paper related to ballooncopters' flight dynamics, including radio-electronics and information technology.

2. CONTENT TO BE SOLVED

When coupling the balloon body with the drone, the following problems will appear:

+ Structure of the coupling assembly.

+ Balancing force and moment when flying stably.

We will consider the necessity and direction of solving the above problems in turn.

2.1. Assembly structure solution

The idea of coupling 4 rotors to the balloon body has existed for a long time [1], however, it was only recently [3] that the idea of taking advantage of the drone's advantages (easy to manufacture and easy to use) to couple to the balloon body appeared. The problem is how to couple to maximize the drone's use (fewer structural changes) and less intervention in the drone's thrust vector control system. Drone manufacturing technology has been perfected for decades, so it is necessary to limit intervention in the drone.

To couple the balloon body and the drone while still ensuring their relative independence, we use the ball joint (figure 7). The ball joint needs to allow the drone to tilt (3-angle control), as when flying independently, reducing the torque required many times for the drone to create many times when needing to control the thrust vector (figure 4), while not having to interfere with the 3-angle control system of the thrust vector.

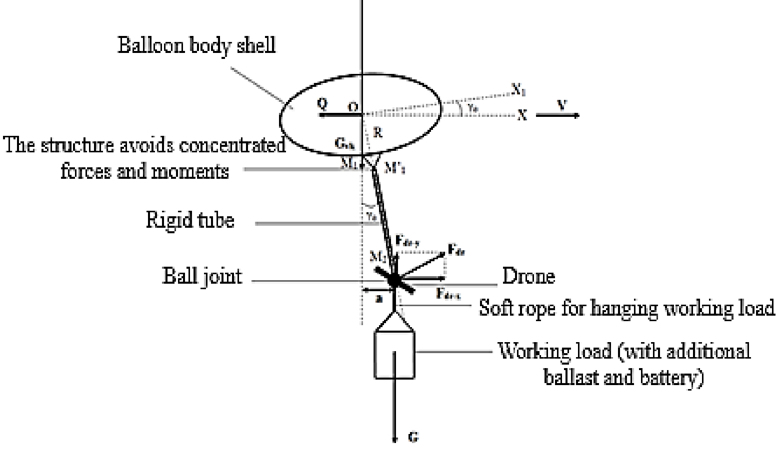

Figure 7. Diagram of connecting the balloon body to the drone.

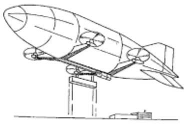

Figure 8a

Figure 8b

Figure 8. *The idea of combining a balloon and 4 rotors.*

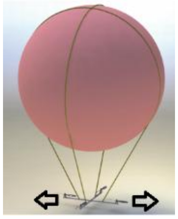

Figure 9a. *Concept of suspending a drone with a flexible wire under the balloon body (Italy, 2017).*

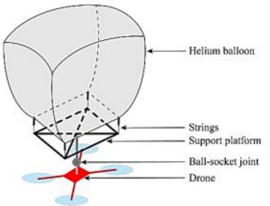

Figure 9b. *Proposed coupling of drone and balloon body (US-2022).*

Figure 9c. *Three-degree-of-freedom spherical joint.*

As we know, the minimum condition for a flying vehicle to fly stably is to have a balance of forces and moments. Below, we will consider the balance of vertical and longitudinal forces, then consider the balance of moments. Here, we only consider static balance (speed, altitude, and angles are all constant).

2.2. Vertical balance: Archimedes force and ballast load

Unlike conventional aircraft, the outdoor temperature directly changes the air density and directly affects the total take-off weight. Therefore, before take-off, ballast must be used to counterbalance the buoyancy force.

Obviously, from the vertical force equilibrium condition, we have:

$$\mathbf{P_a + F_y = G_{vo} + G_{dr} + G_{od} + G_{ct}} \qquad (1)$$

in there:

+ Archimedes buoyancy, [N]: $P_a = k_{no}Vol.(\rho_{H2000} - \rho_{heli}).g$;

+ Coefficient k_{no} takes into account expansion (increase in volume due to the balloon body expanding as it rises $H = H_{max}$).

+ Vol- Balloon volume, m^3; ρ_{Hmax} – Air density at altitude $H = H_{max}$ [kg/m^3]; ρ_{heli} – Helium density, $\rho_{heli} = 0,16\ kg/m^3$; $g = 9,8\ m/s^2$;

+ Shell weight, [N], $G_{vo} = 2,04.S_{xq}$; S_{xq} is the area around, [m^2], coefficient 2,04 N/m^2 is taken from the sphere of the Union level topic. When R = 2,1 m (figure 15) then $G_{vỏ} = 234$ N (same material PVC 0,14 mm);

+ G_{dr}: Prototype drone self weight S50 (generate force max 900N), $G_{dr} = 262$ N (including 01 battery pack 130 N), if including camera + television system and data transmission, then add 15 N, according to partner's data;

+ G_{od}: Weight of the vertical tail assembly for stabilization and assembly details (lightweight material), tentatively calculated for the example below 30 N;

+ G_{ct}: Working load (may include ballast load G_d and additional battery $G_{pin\_additional}$, if camera + video transmission system is already installed, it is not included in G_{ct} load);

+ $F_{dr\text{-}y}$: Vertical component of tensile force F_{dr} (figure 4). This force needs to be selected ≥ 5% of total weight (~ 50 N) to ensure that the altitude control force can be negative when necessary.

On the other hand, this force is a consequence of the force F_z, which must be balanced by the aerodynamic force to avoid drifting in the horizontal plane, which must be equal to the aerodynamic force Q_{max}, from the horizontal equilibrium condition:

$$F_z = F\sin(\gamma) \geq Q_{max} \tag{2}$$

where α is the tilt angle of the drone (figure 4), for example, $\alpha_{max} = 60^0$ (maximum tilt - according to the supplier).

2.3. Longitudinal force balance

Obviously, if the balloon body is spherical, the drag coefficient is quite large ($C_x \sim 0{,}4$), but because it is easy to manufacture and easy to control [1], it is still sometimes used, for example, in the project of the Vietnam Union of Science and Technology Associations. Figure 10 is a photo taken during the demonstration flight at the end of the project 2018. Therefore, it is necessary to reduce the drag coefficient, if you want to increase the wind resistance, you need to reduce the drag coefficient C_x, you need to choose an aerodynamic shape for the balloon body.

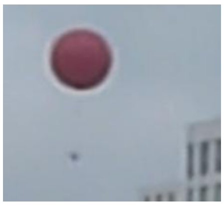

Figure 10. *BH is flying on demonstration at the Institute of Space Technology.*

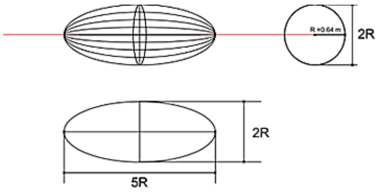

Figure 11. *Example of an oval balloon body shape with a coefficient Cx halved.*

Figure 12 shows the speed triangle: the ground velocity vector V_g, the wind vector W, and the zero velocity vector Va. Thus, the BH needs to turn its nose in the direction coinciding with the air velocity vector while still moving according to the ground velocity vector.

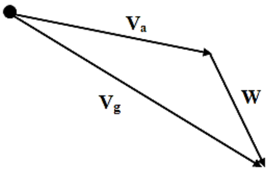

Figure 12. *Air velocity vector V_a and ground velocity V_g when there is wind W.*

From the vertical and longitudinal force balance items, we see that increasing the size will carry more weight, but at the same time, the aerodynamic force (wind impact) will be stronger. However, the ability to carry weight is proportional to the cube of the size of the balloon body, while the aerodynamic force is only proportional to the quadratic. Therefore, we see that most airships are made very large.

2.4. Moment balance in the direction of the BH

When there is wind, for example, a crosswind that pushes the BH (and the drone) to the right, as mentioned in the drone section in section 1, due to the sensor, the control system will tilt to the left, creating a force $F_{dr\text{-}z}$ to counteract the aerodynamic force F_{az} (figure 4). If the wind remains constant after that, the forces $F_{dr\text{-}z}$ and F_{az} will be balanced, but the moment will not be balanced (figure 7) because there is a non-zero side slip angle $\beta \neq 0$ (figure 14).

The directional stability of a flying vehicle is the ability to self-cancel the edge slip angle ($\beta \rightarrow 0$). For the BH, in practice, the BH is often "self-selected", that is, it has aerodynamic stability or the aerodynamic center is behind the center of mass: $X_{Fz} = -M_y/F_{az} < 0$.

The following is an example of calculating the aerodynamic center position of the BH with aerodynamic shape and dimensions as shown in figure 1 (balloon body length L = 5R = 10.5 m, largest cross-sectional diameter D = 2R = 4.2 m, R = 2.1 m) using the discrete vortex method. The calculation grid results and aerodynamic center position are as follows:

Aerodynamic center result (dimensionless): $\overline{x}_F = 0.491$ (compared to the BH fuselage tip). From that, we can deduce that the aerodynamic center position is 49.1% from the BH fuselage tip. Thus, the BH is unstable, so we have to increase the vertical tail area to "pull" the aerodynamic center back so that the aerodynamic center is behind the center of mass (ie. $\overline{x}_F$ is about 54% larger).

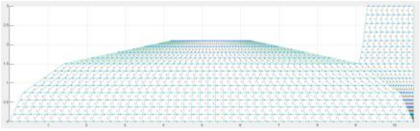

Figure 13. *The mesh of half of the balloon body is symmetrical about the x-axis.*

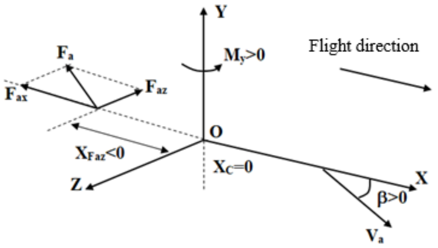

Figure 14. *Coordinate system and sign rule when considering moment equilibrium.*

2.5. Moment equilibrium in the XOY plane of the BH

When the balloon body pitches up, a lever arm appears (figure 7), creating a moment of force P_a, and a part of gravity tends to reduce the pitch angle γ. If this angle is large, it will increase the aerodynamic force. Therefore, it is necessary to make $\gamma \to 0$ by moving the suspension point forward. It is clear that the force system must be balanced:

$$(\vec{P}_a, \vec{Q}, \vec{G}_{vkc}, \vec{F}_{dr}, \vec{G}) \sim 0 \tag{3}$$

Then the balloon body will be tilted up at an angle γ_o and we take the moment of the force system (2.3) with respect to point O of the balloon body to get the following expression to determine the angle γ_o:

$$\sum \overline{m}_O(\vec{F}_k) = F_x.OM_2.\cos\gamma_o - (G - F_{dr-y}).OM_2.\sin\gamma_o = 0$$

$$\to tg\gamma_o = \frac{F_x}{G - F_{dr-y}} = \frac{Q}{G - F_{dr-y}} \tag{4}$$

Assuming that the BH flies stably with a velocity of V = 4 m/s at an altitude of H = 2000 m, then the aerodynamic drag force acting on the BH body is calculated according to the formula:

$$Q = 0.5.C_x.\rho.V^2.S \tag{5}$$

with $C_x = 0.2$, $S = \pi R^2$, $R = 2.1$ m, $\rho = 0.922$ kg/m^3.

Substitute the calculated number Q = 20.5 N.

At the same time, with the input data of the BH as presented in section 2.2, we can calculate $G\text{-}F_{dr-y} = 234$ N. From there, we deduce $\gamma_o \approx 5^0$ (figure 7). As mentioned, it is necessary to move the suspension point forward.

2.6. Examples of the BH application in forest protection

Figure 15 shows the diagram of the forest protection support system: BVR-100 system.

Key features of BVR-100:

+ Function: Support forest fire/deforestation detection.

+ Productivity (observed area in one hour): 5000 ha/h.

+ Patrol flight altitude (well beyond the reach of criminals' weapons): 2000 m.

+ Patrol flight speed: 18 km/h (like cycling).

+ Maximum flight speed: 50 km/h.

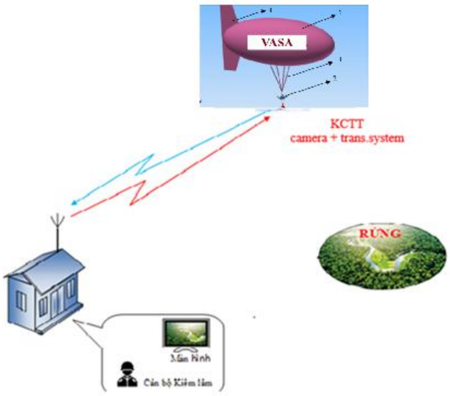

Figure 15. *Diagram of the remote ranger support system.*

+ Balloon body: Oval, circular cross-section R = 2.1 m; length 10.5 m; volume nearly 100 m^3, helium gas must be added once every 3 days, no more than 5%.

+ Drone: 6 rotors, maximum force 90 kgf, battery operated, built-in 30X camera, 3-axis stabilization, day/night observation, live TV, 20 km range.

+ Camera control: Manual/automatic by program.

+ The area being scanned is displayed on the map. When necessary, the altitude can be lowered for clearer observation. When necessary, a photo can be taken with the time and location clearly recorded.

+ Hanging flight time (calm wind): 6 h.

+ Hanging flight time (light wind 7 km/h): 5 h.

+ Compared to all existing battery-powered drones (including HERA exported to the US by Luong Viet Quoc), they can only fly for no more than 40 minutes (unloaded, one takeoff and landing).

+ Take-off and landing: Vertical, so there is no need for surrounding space (clearance zone).

+ Field: 15 m x 15 m, normal ground (a little wider than a volleyball court).

+ Manual/automatic flight control.

+ Maximum wind – level 6 ($\leq$ 50 km/h).

+ Can fly at night.

+ Operated by 1 intermediate electromechanical employee, training < 1 week.

+ Storage: Tarpaulin is used to protect against the sun, rain, and wind. It is box-shaped and 13 x 6 x 7 m.

2.7. Forecasting the demand and effectiveness of the BH application

With the ability to carry heavy loads with negligible emissions and a very high level of automation, the BH not only sprays pesticides like agricultural drones, but also performs seeding and foliar fertilization in high-tech agriculture with very low emissions. Moreover, the BH can effectively serve the cause of hunger eradication and poverty reduction in remote areas where road construction is uneconomical, providing great support for e-commerce (shipping goods through mountainous areas to the gathering place or vice versa, for example, to/from cities).

The BH can be a powerful assistant for law enforcement agencies, traffic surveillance, and anti-smuggling. With the ability to fly at night and almost invisible (no radar reflection and no heat radiation, flying high beyond the range of infantry fire and flying smoothly) and being able to be equipped with AI, the BH can be widely applied in the military, as suicide robots, reconnaissance, information relay, serving to protect borders, islands, etc.

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3. CONCLUSIONS

Ballooncopters are a new type of flight vehicle, opening up many prospects for Vietnam to be a country that "stands shoulder to shoulder with the world's great powers" in aerospace technology. We cannot compete with countries like the US, China, and Russia in manufacturing fast, high-flying vehicles, but we can compete successfully in niche markets: vertical take-off and landing, slow flight, and environmentally friendly. These flying products are especially easy to manufacture, almost risk-free when testing in flight, easy to use, and have a very large market demand.

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TÓM TẮT

Khí cầu trực thăng – Một loại UAV mới có nhiều triển vọng

Trong những năm gần đây, chúng ta thấy nhu cầu ngày càng tăng đối với các loại UAV dễ sản xuất và dễ sử dụng. Đồng thời, yêu cầu giảm phát thải (ứng dụng công nghệ “xanh”) cũng trở lên ngày càng cấp thiết. Bài báo đề xuất một giải pháp kết hợp giữa khí cầu và trực thăng nhằm phát huy các ưu điểm của thiết bị bay nhiều cánh quạt (drone) và khí cầu để đáp ứng các yêu cầu nói trên. Đồng thời, bài báo cũng đề xuất các giải pháp nhằm khắc phục các vấn đề cơ khí phát sinh khi lắp ghép thân khí cầu với drone, các ví dụ minh họa như bảo vệ rừng và một số khả năng ứng dụng khác.

Từ khóa: Phương tiện bay; Drone; Khinh khí cầu; Giám sát từ xa; Trực thăng.