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Detection of Three-Dimensional Center of Gravity for Flight Stability Analysis of Drones

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ABSTRACT
Drones have attracted widespread attention in recent years. Although the aerial photography function of drones is widely known at present, in the future, drones will play a role in a variety of fields such as construction and agriculture. The application of drones to the logistics and transport industry is also a subject that has been under scrutiny. Drones can greatly reduce delivery and labor costs, while enabling the delivery of goods in a shorter period. However, there are still many issues that need to be resolved in order to realize drone logistics. The most important of these is the safety of drones during flight transport. Because of the position of the cargo's center of gravity or wind interference, drones may lose their balance during flight. An important invention by the second author of this paper provides a good idea to solve the problem in this research. Since both ships and drones are floating objects, by applying the theory of Detection of Three-Dimensional Center of Gravity (D3DCG) for ships to drones, a way to detect the stability of the center of gravity of drones in flight is obtained. Meanwhile, the flight stability of the drone under different loads is verified through empirical experiments. The results proved that the D3DCG theory applied to drones is valuable for the real-time detection of the safety state of drones during flight maneuvers. This result will greatly contribute to the prevention of drone flight accidents.
Keywords - Drone, stability, Vibration of moving body, Natural frequency, D3DCG

I. INTRODUCTION

The importance of research in the realm of drone stability cannot be overstated due to its capacity to safeguard and optimize the function of drones, amplify their potentialities, and advocate for their diverse application. Therefore, it is incumbent upon us to sustain the advancement of drone technology through rigorous research, paving the way for its broader application across various fields.

In the process of research on drone path simulation (2023), The authors delved into the intricate simulation of drug delivery trajectories for Unmanned Aerial Vehicles (UAVs). The intention was to translate these theoretical simulations into tangible applications. Nonetheless, during the real-life flight trials with compact drones, a significant hurdle surfaced: even while bearing relatively lightweight pharmaceutical cargo, the drones exhibited flight instability (figure 1). In order to overcome this obstacle and augment the practicality of the simulation model, the authors embarked on empirical investigation and experimentation around drone stability. Within this framework, the authors incorporated the D3DCG theory as a strategy to fortify flight control and facilitate smoother operations. Moreover, emphasizing drone stability could play a pivotal role in optimizing the successful deployment of drones in drug delivery systems.

The instability of drone flight is a critical issue that demands attention. The theory of Detection of Three-Dimensional Center of Gravity (D3DCG) has been gaining traction as a cost-effective measure to avert rollover accidents. Watanabe (2011) was the innovator behind D3DCG, initially developed to avert rollover accidents involving trailer trucks hauling containers. The methodology allows for the determination of the center of gravity's height by solving a quadratic equation. As delineated in this paper, the system entails a relatively low cost of approximately US$500 for hardware components, primarily made up of a mobile PC and an A-D converter, excluding the sensor.

Subsequent studies have applied the D3DCG theory to various contexts. Kawashima et al. (2013) studied its application for railway cars, specifically for detecting coil spring deterioration. Similarly, Kohinata et al. (2020) used D3DCG to analyze bodies under ambulatory conditions, determining the center of gravity from the frequency of heaving and rolling in walking motions. Noteworthy was their investigation into the walking patterns of different age and gender groups. Dang et al. (2016) validated the theory's applicability to trucks transporting marine containers during travel. The D3DCG theory, a culmination of years of research, has been applied to diverse fields including healthcare, eldercare, sports, and autonomous driving. This has facilitated practical advancements across these domains, thereby enhancing safety in each field.

Figure 1. the unstable flight of drone

II. METHODOLOGY

2.1The basic equation of the D3DCG Theory

In order to study the flight stability of drones, the first step is to start with the theoretical derivation and analysis. The derivation of the D3DCG theory, which is important in this study, is presented. The formulation of the vertical oscillation (Heaving) of a center of gravity detection object on an elastic structure is given by equation (1).

$$T' = 2\pi\sqrt{\frac{m}{2k}} \tag{1}$$

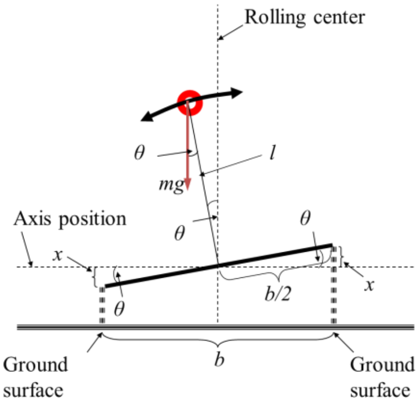


Figure 2. the basic principle of D3DCG theory

T' : Cycle of heaving,

k : Spring coefficient of one of the left and right sides of the elastic structure,

m：mass,

π：circumference,

The relationship between the rotational moment and the force balance during rolling is equation (2).

$$lf = -kxb + mgl\sin\theta \tag{2}$$

Were,

f: Force toward tangent line at the center of gravity,

g :Acceleration of gravity,

θ :Angle of rolling,

l :Height of the center of gravity from the axis of rolling,

b : Length between springs,

x ： Vertical deviation at each springs.

Where, $x = \frac{b}{2}\sin\theta$

Therefore, substituting into equation (2), we obtain equation (3).

$$f = -\frac{m}{l}\left(\frac{kb^2}{2m} - gl\right)\sin\theta \tag{3}$$

Here, the value of the rolling angle θ is a fine one of a few degrees. If θ is sufficiently small from the properties of the trigonometric functions, equation (3) can be rewritten into equation (4), as sinθ can be written as θ.

$$f = -\frac{m}{l}\left(\frac{kb^2}{2m} - gl\right)\theta \tag{4}$$

Equation (4) can be rewritten as follows, since it is equivalent to the equation for circular motion with l as the radius.

$$ml\frac{d^2\theta}{dt} = f = -\frac{m}{l}\left(\frac{kb^2}{2m} - gl\right)\theta \tag{5}$$

$$\frac{d^2\theta}{dt} = -\frac{1}{l^2}\left(\frac{kb^2}{2m} - gl\right)\theta \tag{6}$$

Here, the phase of θ is put at ω.

$$\frac{d^2\theta}{dt} = -\omega^2\theta \tag{7}$$

$$\omega = \frac{1}{l}\sqrt{\frac{kb^2}{2m} - gl} \tag{8}$$

Since the frequency can be obtained as the reciprocal of the period, the vertical oscillation frequency v' and the horizontal oscillation frequency v corresponding to the vertical oscillation period T' and the horizontal oscillation period T in equation (1) can be put as equations (9) and (10).

$$v' = \frac{1}{2\pi}\sqrt{\frac{2k}{m}} \tag{9}$$

$$v = \frac{\sqrt{\frac{kb^2}{2m} - gl}}{2\pi l} \tag{10}$$

Comparing equations (9) and (10), if v' and v are known, the two unknowns are l and k/m, which can be solved analytically. Equation (9) can be rewritten into equation (11) and equation (10) into equation (11).

$$\frac{k}{m} = 2\pi^2 v'^2 \tag{11}$$

$$4\pi^2 l^2 v^2 = \frac{kb^2}{2m} - gl \tag{12}$$

Substituting equation (11) into equation (12), we obtain equation (13), which is the D3DCG detection theory equation.

$$l^2 + \frac{g}{4\pi^2 v^2} l - \frac{b^2 v'^2}{4v^2} = 0 \tag{13}$$

Equation (13) is a quadratic equation by l, so the height of the center of gravity, l, is obtained.

2.2 the Calculation of the limit position of the center of gravity

From the derivation of the D3DCG theory, the height of the center of gravity, l, could be determined. The next step is to calculate the center-of-gravity limit position at which the spring structure will always overturn. Equation (14) is satisfied when f in equation (3) is the restoring force against gravity. The spring constant k is 2k in equation (1), since there are two symmetrical pairs of the same spring. We can note that a spring in D3DCG does not indicate a specific part constituting an elastic structure, but the part that comprehensively functions elastically to support the center-of-gravity detection object is treated as a single spring.

$$\frac{kb^2}{2m} - gl > 0 \tag{14}$$

Therefore, if the critical height at which the object reaches overturning is l_{max}, equation (15) is satisfied.

$$l_{max} = \frac{kb^2}{2mg} \tag{15}$$

Substituting equation (9) into equation (14), equation (16) is established.

$$l_{max} = \frac{\pi^2 v'^2 b^2}{g} \tag{16}$$

It was found that the height of the center of gravity l_{max} leading to overturning of the object is determined by the natural vibration frequency v' in the vertical direction and the length b of the width of the spring structure l/l_{max} gives the percentage of the object to the limit height, which is an indicator of the stability of the object The smaller l/l_{max}, the more stable the object is.

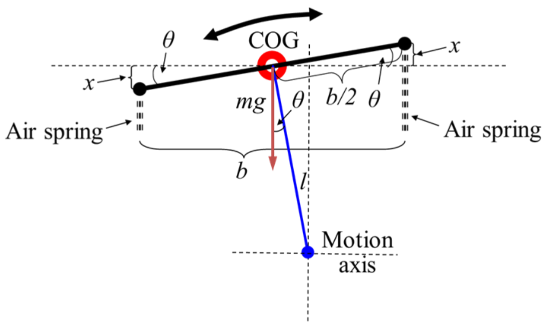


Figure 3 Theoretical diagram of D3DCG for a drone in levitation.

2.3 the Calculation of the limit position of the center of gravity

From The D3DCG theory in the field of levitation is an application of the land-based the D3DCG theory that can be used for objects floating on water, such as ships. The figure shows an image of the oscillation of a ship on the surface of the water. As shown in the figure, a floating ship has an axis of motion separate from its center of gravity, and swaying is caused by the effect of the axis of motion. The fluctuations in the water to which the ship is subjected on the sea surface are in a state of real-time change, the spring (b) of the ship is also a variable that changes at any time. Same as ship, the drone flying in the air is also in a levitation. It should be noted that, Different from previous studies (trucks, the human body).

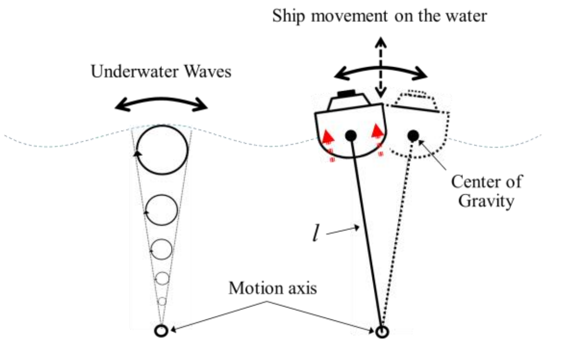


Figure 4 Theory of D3DCG during levitation

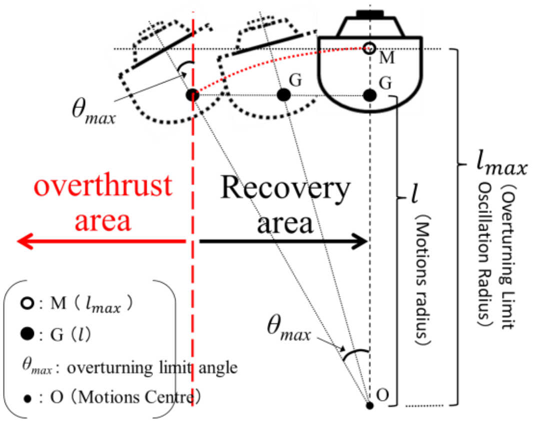


Figure 5 Imaged figure of capsizing limit of a ship

The figure shows the overturn and recovery regions of a vessel. The overturning limit angle θ_{max} is the angle that indicates the boundary between overturning and recovery. The figure shows that the overturning limit swing radius of a ship corresponds to the overturning limit height l_{max} of the D3DCG theory on land. In addition, the width of the restoration region shown in the figure, i.e., the width of the perpendicular line passing through the center of gravity G in a ship that is not inclined and the perpendicular line passing through the center of gravity G in a ship inclined to the boundary between overturning and restoration, can be regarded as 1/2 of the spring width b.

$$\text{lmax}^2 = \left(\frac{b}{2}\right)^2 + l^2 \tag{17}$$

$$\cos\theta_{max} = \frac{l}{lmax} \tag{18}$$

$$b^2 = \frac{4v^2}{v'^2} l^2 - \frac{g}{\pi^2 v'^2} l \quad (19)$$

$$\frac{b^2}{4} = \frac{\pi^4 v'^4 b^4}{g^2} - l^2 \quad (20)$$

$$\frac{16\pi^4 v^4}{g^2} l^3 + \frac{8\pi^2 v^2}{g} l^2 - \frac{v^2}{v'^2} l - \frac{g}{4\pi^2 v'^2} = 0 \quad (21)$$

$$l^3 + \frac{g}{2\pi^2 v^2} l^2 - \frac{g^2}{16\pi^4 v^2 v'^2} l - \frac{g^3}{64\pi^6 v^4 v'^2} = 0 \quad (22)$$

Therefore, the relationship between the swing radius l, the overturning limit swing radius l_{max}, and the width b can be expressed as in Equation (22).

III. EMPIRICAL EXPERIMENT

The parameters of drone empirical experiment are as follows, HOLY STONE HS120D was used, which weight is 221g (without camera :198g). The maximum flight distance is 984 feet. The size is 270mm*270mm*120mm.The width between propellers is 15cm. Measurements were taken with the drone hovering at a height of 5 m for approximately 1 minute.

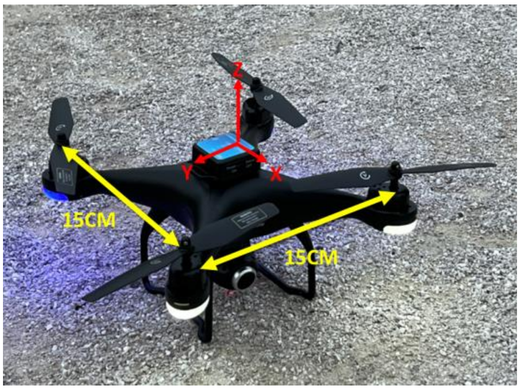


Figure 6 Experiment devices used for experiments

Figure 7 Configuration of medicines during medicine transportation experiments (Exp.2 to 9).

The drone low weight medicines cargo flight experiments were analyzed using the derived levitation weight center detection theory equation to verify the applicability of the levitation weight center detection theory. The equation (22) was used in analysis the dataset. The spring width b and the critical rollover angle θ_{max}, which are variable in D3DCG theory of the levitation, were also analyzed.

Table 1 The load details for simulation experiments

Exp.	Carrying items	Weight(g)
1	Blank comparison group	0
2	Medicine*1(10g*1)	10
3	Medicine*2(10g*2)	20
4	Medicine*3(10g*3)	30
5	Medicine*4(10g*4)	40
6	Medicine*5(10g*5)	50
7	Medicine*6(10g*6)	60
8	Medicine*7(10g*7)	70
9	Medicine*8(10g*8)	80

IV. THE FREQUENCY ANALYSIS AND RESULT

The vertical acceleration and horizontal angular velocity of the experimental apparatus were obtained by the sensors of the oscillation measurement system. The sampling frequency of the sensor used in the experiment was 200 Hz. The data of acceleration in the vertical direction is shown in the Figure 8. The fast Fourier transform (FFT) analysis of the figure is shown in the Figure 9. The peak frequency which in the red circle was specified as a frequency intrinsic to the center of gravity of the drone. The table shows the results of the drone weight cargo flight experiment analyzed by the levitation D3DCG equation. The relationship between the rollover risk and pseudo-cargo weight is shown in Figure 10.

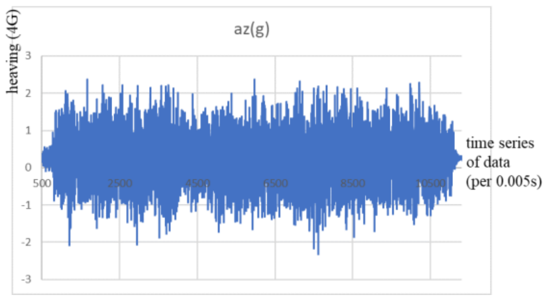
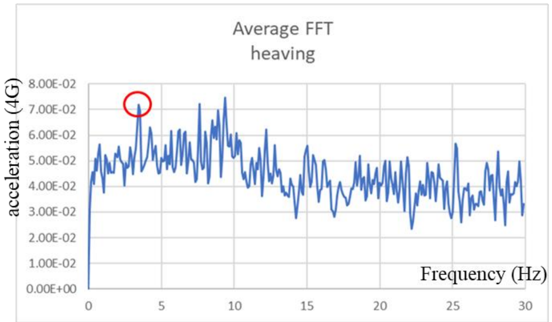
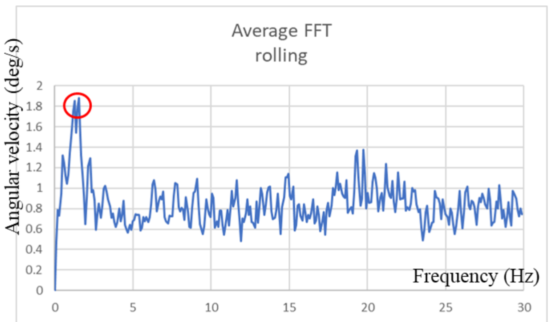


Figure 8 The data of experiments (Exp. 2)



(a)The heaving data



(b)The rolling data

Figure 9 The Average FFT of Heaving and Rolling data (Exp. 2).

Table 2 The results for experiments of static flight stability (l/l_{max})

No	*load weight* (g)	*Heaving* (Hz)	*Rolling* (Hz)	l	l_{max}	l/l_{max}
1	0	2.441	1.800	0.03	0.04	73.2%
2	10	1.360	0.810	0.12	0.16	75.6%
3	20	2.670	1.560	0.03	0.04	75.9%
4	30	4.130	2.208	0.02	0.02	77.1%
5	40	2.410	1.426	0.04	0.05	75.7%
6	50	3.020	1.953	0.02	0.03	76.2%
7	60	3.510	1.810	0.02	0.03	77.0%
8	70	3.710	2.050	0.02	0.02	79.0%
9	80	3.810	1.460	0.03	0.03	81.5%

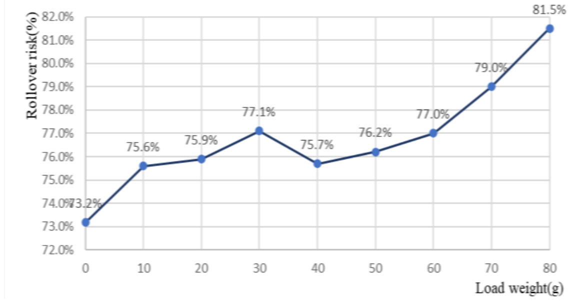


Figure 10 The relationship of load weight and rollover risk.

V. CONCLUSION

Figure 10 shows the relationship between l/l_{max} and pseudo load weight plotted according to Table 2. From Figure 10, it can be confirmed that as the pseudo load weight increases, l/l_{max} also increases; the closer the value of l/l_{max} is to 1, the more unstable the drone is. It is found that the D3DCG theory can be applied to drones.

The results of experiments lead to this conclusion, the greater the weight of the loaded goods, the easier it is to approach the rollover. Another conclusion is, even if under the same experimental setting, the heaving data is not easily analyzed for direct use because the sensors are affected by the GPS transmitters and magnetic fields that come with the drones. Therefore, it is important to next investigate how to remove the influence of the sensor versus analyzing the stability data during motion.

Acknowledgements

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REFERENCES

[1] Watanabe Y. Three-dimensional center of gravity detections for preventing rollover accidents of trailer trucks hauling containers[J]. Open Journal of Mechanical Engineering, 2017, 2(1): 11.

[2] Yutaka Watanabe: Capsize risk level calculation system, US patent application NO. 14401471, 2014

[3] Yutaka Watanabe, Takenaka Civil Engineering & Construction Co., Ltd, Determination Device and Posture Control Device.No.PCT/JP2020/004615, 12.08.2021.

[4] Risao Kohinata, Watanabe, "Measurement of physical fatigue by detecting the center of gravity of human body", Safety Problems Symposium of the Civil Engineering Society '20, Proceedings Decision Economy, Proceedings of the Transport and Logistics Division Conference, vol. 2020.29:2005

[5] Kawashima S, Watanabe Y. Detection of the Three-Dimensional Center of Gravity on A Moving Automobile[J]. Journal of the Japan Packaging Institute, 2014, 23(3): 203-213.

[6] Kawashima S, Watanabe Y. Center of gravity detection for railway cars[J]. Open Journal of Mechanical Engineering, 2016, 1(1): 8.

[7] Kawashima S, Watanabe Y. Basic research on the relationship between vehicle center of gravity and track disturbance.[J]. Proceedings of the Transport and Logistics Division Conference, 2018.27, 2018: 3111.

[8] Dang R, Watanabe Y. Three-Dimensional Center of Gravity Detection for Trucks Hauling Marine Containers[C]//International Forum on Shipping, Ports and Airports (IFSPA) 2015: Empowering Excellence in Maritime and Air Logistics: Innovation Management and Technology Hong Kong Polytechnic University. 2016.

[9] Shan XU, WATANABE Y. Three-Dimensional Path Planning of UAVs in Complex Urban Terrains: A Case Study of Emergency Medicine Delivery in Shanghai (China)[J]. Toros Üniversitesi İİSBF Sosyal Bilimler Dergisi, 9(Special Issue 2nd International Symposium of Sustainable Logistics “Circular Economy”): 65-78.