

Intelligent passively stabilized quadrotor

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Abstract. Quadrotor stability is one of the most topical researches worldwide. It is due to the simplicity, availability and cost of such platform. This miniature aerial vehicle is highly manoeuvrable, straight forward to use and to maintain. It can be deployed to perform wide variety of tasks. On the other hand, the quadrotor suffers from non-stability, which makes it unreliable, especially when flying on low speed, high altitude and in windy circumstances. This paper discusses the improvement of the quadrotor by adding a stabilizing mechanism working as a passive breaking system in sharp and spontaneous turns. The mechanism is described and simulated as a standalone module. The end result represents the determination of the stiffness coefficient of the stabilizing actuator using fuzzy logic controller.

1. Introduction

Researching and optimizing Unmanned Aerial Vehicles (UAVs) is very topical. It is due to the developed commercial potential of this market, which lead to their exploitation for civil tasks. Traditionally UAV are used in the military field. However, nowadays, UAVs are being deployed into cinematographic, rescue, exploration and delivery tasks. UAVs are classified according to their type, size and tasks designed for. A rotorcraft type such as quadrotor is affordable products, easy to operate and maintain and does not require supporting infrastructures. As a vertical take-off and landing UAV, the quadrotor can start from any place and land without any difficulties. The maneuverability of the quadrotor is a major benefit. This simple UAV is used for landscaping, scanning high-rise buildings and monitoring. On the other hand, the low flight range, fragile chassis in comparison to other UAVs, and its non-stability; especially when flying at high altitude or in windy circumstances minimize the tasks variety, where it can be deployed.

Many researches concentrate on optimizing the control systems, construction materials, path planning algorithms and generation of adequate mathematical models of the quadrotor. Our contribution to this topic is not far from the worldwide tendency. This paper describes passive stabilization mechanism for the quadrotor. The mechanical components to realize the idea and the control scheme are discussed in paragraph 3, simulations and results in paragraph 4. While the bibliographic review on the subject matter is addressed in paragraph 2.

2. Literature review

Stability is one of the major drawbacks of the vertical take-off and landing (VTOL) UAV rotorcraft. Basically, this is due to the flying mechanism generating the lifting force. The quadrotor has 6-degree of freedom, obtained from four rotors working in couple, thus to execute four flight regimes: roll, pitch, yaw and hover. The first three describe the rotational movement of the quadrotor with reference to $O_B X_B Y_B Z_B$ or Body-axis, and the latter represents the vertical movement or flight altitude. The



equations of motion of the quadrotor are introduced in equations (1-6):

$$\ddot{X} = (\sin\psi\sin\theta + \cos\psi\sin\theta\cos\varphi) \frac{U_1}{m}; \quad (1)$$

$$\ddot{Y} = (-\cos\psi\sin\varphi + \sin\psi\sin\theta\cos\varphi) \frac{U_1}{m}; \quad (2)$$

$$\ddot{Z} = -g + (\cos\theta\cos\varphi) \frac{U_1}{m}; \quad (3)$$

$$\dot{p} = \frac{I_{YY} - I_{ZZ}}{I_{XX}} q r - \frac{J_{TP}}{I_{XX}} q \Omega + \frac{U_2}{I_{XX}}; \quad (4)$$

$$\dot{q} = \frac{I_{ZZ} - I_{XX}}{I_{YY}} p r - \frac{J_{TP}}{I_{YY}} p \Omega + \frac{U_3}{I_{YY}}; \quad (5)$$

$$\dot{r} = \frac{I_{XX} - I_{YY}}{I_{ZZ}} p q - \frac{J_{TP}}{I_{ZZ}} r \Omega + \frac{U_4}{I_{ZZ}}; \quad (6)$$

where \ddot{X} , \ddot{Y} and \ddot{Z} - the acceleration of the quadrotor in linear movement; φ , θ and ψ - the Euler angles or roll, pitch and yaw respectively; U_1 , U_2 , U_3 and U_4 - the hover, roll, pitch and yaw flight regimes power parameters; I_{XX} , I_{YY} and I_{ZZ} - the projection of the moment of inertia; \dot{p} , \dot{q} and \dot{r} - the projection of the angular velocity of the quadrotor in Body-axis system $O_B X_B Y_B Z_B$; Ω - the rotational velocity of the propellers.

As it can be clearly seen, the linear movement of the quadrotor is generated through the variation of the Euler angles. This creates difficulties when controlling the stability of the flight in windy circumstances, very low and high flight altitude as well as when making sharp turns. These difficulties are major issues to be dealt with in optimization tasks such as determination of shortest path and trajectory planning [1,7-9], coverage based path planning [2,10], or obstacle avoidance [3]

Stability problems are often discussed from cybernetic point of view i.e.: control systems, optimization [13, 14], control algorithms [12]. However, stability can be improved by developing new mechanisms [11]. Passive stabilization is rarely discussed. The reason behind that lies in the sensitivity factor of the regulator: with low sensitive regulator, the mechanism tends to be stiff, slow and reactive with great delay, high sensitive mechanism allows for overshooting during stabilization and increase the deviation from the desired trajectory. Adaptive regulators based on fuzzy logic algorithm can be a trade-off point between the two approaches.

3. Stabilization concept

Few available literatures discussed the flight stabilizing mechanism of a quadrotor. One of the most notable is [5], where, the inventor chose introducing fluid-flow control inside the quadrotor in order to stabilize the flight altitude. The mechanism is based on valve control and operator, sensing the rotation of the quadrotor in two-dimensional representation. Other mechanisms were based on the same approach but aiming to divert the air through perforations using diagonal flaps mounted on the quadrotor [6]. Both approaches stabilize the quadrotor in hovering regime only. However, with the advances in computation technology, micro and nano-electromechanical devices (MEMS / NEMS) and artificial intelligence algorithms, the conversion from automated to autonomous control became reality. This makes single dimensional stabilization outdated and not valid for autonomous tasks.

In view of the abovementioned analysis, this paragraph introduces passive stabilizer adopted for high-rise structures deflecting the impact of seismic loads, thus to be used for quadrotor stabilization. The mechanism, depicted in fig.1 consists of the following: A quadrotor chassis **1** encompassing all necessary components: **2** three-axis gyroscope, controller, actuator, gearbox connected to an arm **3** holding physical mass **5** hooked to the quadrotor chassis using stiff springs **4** and scaling rail **6** the orientation of which depends of the physical mass direction signature.

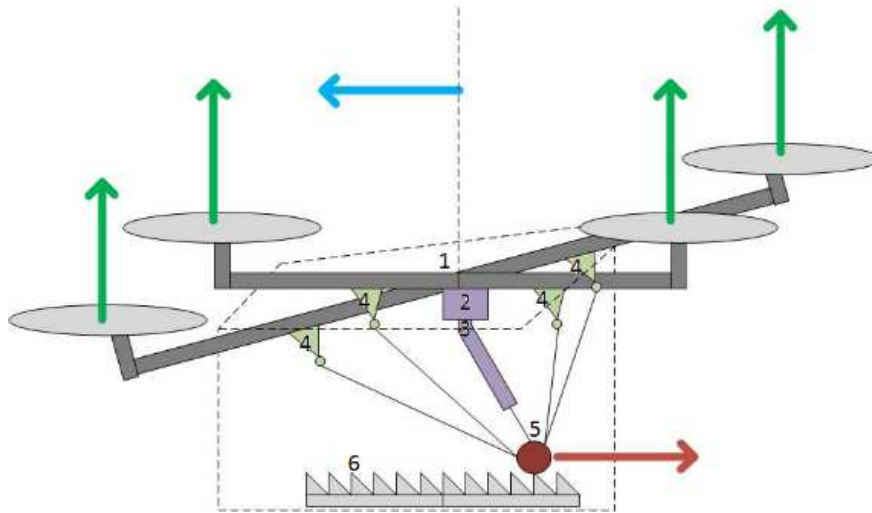


Figure 1. Passive stabilizer of a quadrotor

3.1. Modelling criteria of the passive stabilizer

The mechanism works as follows: as approaching to checking point, the controller receives input on trajectory deviation and start computing the necessary control signal for the actuator beforehand. The same signal causes the actuator to move the arm and to displace the physical mass, which moves in the opposite direction of the deviation signature, i.e.: if the autopilot moves the quadrotor above tolerance limits, the mass has to move in the opposite direction by the same length simultaneously. Here, the controller keeps monitoring the deviation signal and updates the control signal. This mechanism works well for stabilizing the quadrotor in sharp and spontaneous turns, where compensator is needed to cancel the centrifugal acceleration impact. Hence, the main aim of the control task is to regulate the stiffness of the stabilizing mechanism, which will allow the physical mass to move or to remain static. For simulation purposes, it is assumed that the displacement is caused by vibrations occurring at control points of the desired path. The mass of the physical damper (item 5) is assumed to have 10% of the quadrotor total mass. The vibration ratio of the mass is computed using equation (7). The damper vibration should not exceed the displacement vibrations.

$$f_o = \frac{f_d}{f_s} = \frac{1}{1+\mu} < 1; \quad (7)$$

where, f_o - the optimal frequency ratio; f_d - the frequency of the damper; f_s - the frequency of the quadrotor structure and μ - the mass ratio.

Using equation (7), the stiffness equation of the damper can be established:

$$k_d = \frac{\omega_n^2 I_1 I_2}{I_1 + I_2}; \quad (8)$$

where, k_d - the stiffness coefficient; I_1 - the combined inertia of the quadrotor and the actuator; I_2 - the inertia of the mass and ω_n - the natural frequency of the quadrotor. It is assumed that the quadrotor is moving due to the natural frequency; hence, by changing the stiffness coefficient the frequency is controlled at the control points.

3.2. Fuzzy logic controller

Passive stabilization can be obtained in two ways: free and controlled. The first approach leaves physical mass to react freely with occurring vibrations at control points. This causes delayed and unnecessary responses; especially with sharp and spontaneous turns. The latter approach adopts supervised displacement of the mass allowing for more accurate trajectory tracking and just-on-time response. The drawback of such approach is the added weight and energy consumption to activate the passive stabilizer. Since, the optimization criterion is to have accurate positioning, the second

approach is adopted. Controlling the displacement of the mass is suggested by designing fuzzy logic controller (FLC), where, the inputs are the velocity and displacement variation of the quadrotor with reference to the Earth-axis, the output is the stiffness of the stabilizer. Table.1 lists down the fuzzy logic rules of the controller.

Table 1. Determination of stiffness coefficient using

		Fuzzy rules					
V	D	NB	NS	Z	PS	PB	
NB		S	M	M	M	S	
NS		M	L	L	L	M	
Z		M	L	XL	L	M	
PS		M	L	L	L	M	
PB		S	M	M	M	S	

D- displacement, V- velocity, NB, NS, PS, PB, Z are negative big, negative small, positive small and positive big and Zero respectively, S, M, L, XL are small, medium, large and extra-large. It is assumed that the highest deviation in displacement is three times the average length of a commercial quadrotor (0.5 m) and the highest average speed deviation is 10m/s (highest market benchmark 27.2 m/s). The stiffness coefficient varies between [0; 1.5] both limits are inclusive.

The membership functions of the inputs and output are depicted in figure 2.

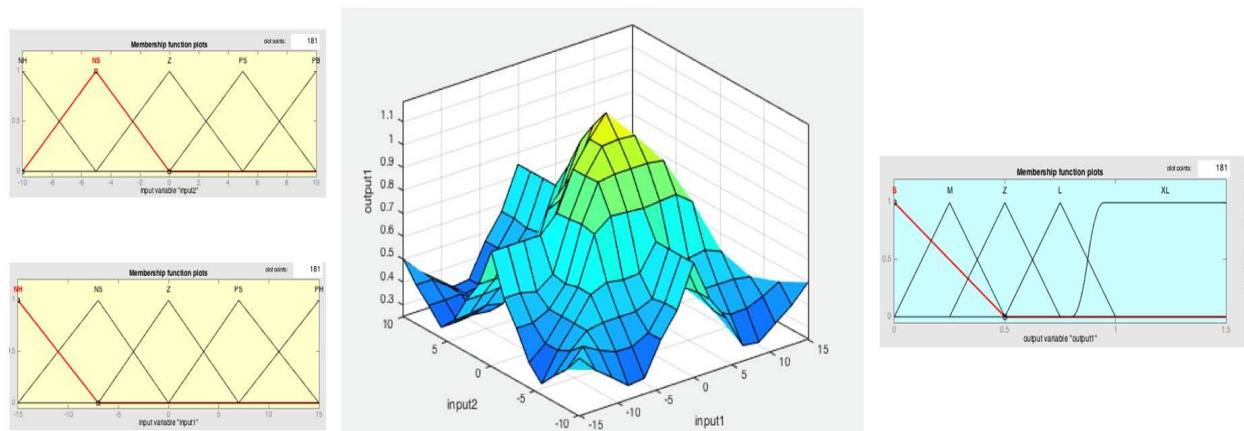


Figure 2. Membership functions of the Fuzzy Logic Controller

4. Simulations results

For simulation purposes, it is assumed that the springs (item 4, fig.2) are extremely synchronized, moving only when the stiffness coefficient is determined, the quadrotor chassis is rigid and does not allow for noisy frequencies, the link between the springs and the physical mass is extremely smooth and light, the quadrotor and the actuator have combined inertia and the physical mass is considered as another body, which performs 2D rotational movement along the axis $O_B Z_B$ in the space plan $O_B X_B Y_B$.

From figure 2, it is clear that the fuzzy rules will allow regulation of the stiffness parameters with upper limit equal to 1. The fuzzy controller is integrated into the control loop of the passive stabilizer mechanism. For simulation purposes, the input of the loop is considered as desired frequency causing the movement of the quadrotor as intimated earlier. The simulation results are depicted in fig. 3.

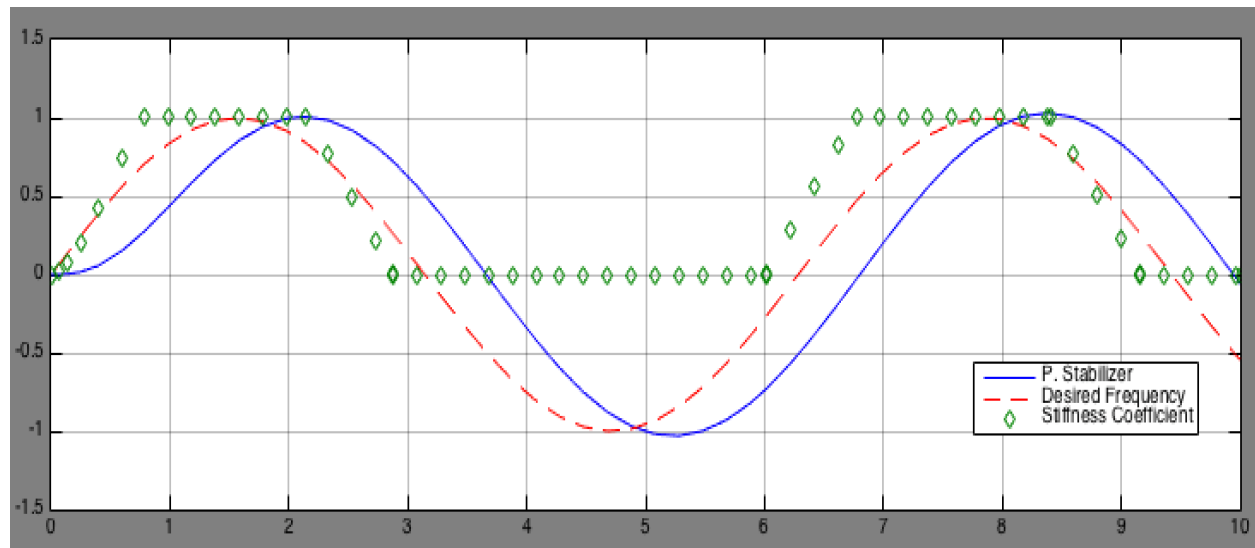


Figure 3. Simulation results for determination of the stiffness coefficient

As it can be seen from the results, the controller was able to determine the stiffness coefficient enabling the actuator to work with the same frequency as desired input. In reality, the frequency should represent the movement of the physical mass, which should serve as a passive stabilizer or breaking system for the quadrotor at selected control points on the trajectory.

On the other hand, the overall picture and the efficiency of the mechanism cannot be evaluated separately. Moreover, the delay in phase between the desired frequency (red) and the obtained results (blue) will definitely have an impact in real-time flight. However, the results obtained serve the purpose for module or subsystem modelling. In addition, the stiffness coefficient determination was perfectly managed.

This work will require future continuation to analyze the impact of the phase delay, whether it can be neglected with reference to the overall control process time of realizing single flight regime, or it will cause additional hindrance and complications.

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