Experimenting with Variable Arm Quadrotors: Realizing Dynamic Configurations for Enhanced Flight Performance

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Abstract

This paper introduces two innovative concepts for variable arms designed for a quadrotor, enabling precise control of its movement through manipulation of the bending moment via varying arm lengths. The primary objective of this research is to develop and identify the most suitable variable arm configuration that facilitates smooth and stable quadrotor movement. The study delves into two concept designs that are well-suited for the quadrotor application. By employing a suitable variable arm, the quadrotor's maneuverability can be effectively regulated based on the bending moment adjustments made possible by the variable arm. Ultimately, the paper presents the design and performance testing of two types of variable arms. The obtained results confirm that the variable arm of the electric actuator with linear guide-Type 2 exhibits smooth and stable movement.

Keywords: Variable Arm, Quadrotor, Dynamic Configuration, Flight Performance

1. Introduction

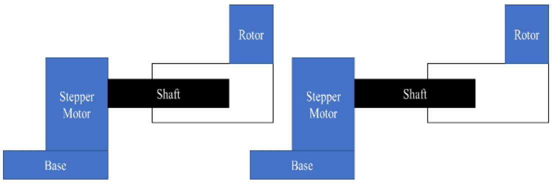
The quadrotor, a type of UAV (unmanned aerial vehicle), holds great potential for overcoming terrestrial challenges [1], leading to its widespread use in various industrial and commercial applications such as geographic mapping, surveillance, agricultural tasks like fertilization or pesticide application, and aerial photography [2]. This continuous utilization has spurred the development of the quadrotor to enhance its stability, performance, and multimodal capabilities [3]. Typically, quadrotors are designed with four rotors, positioned at the vertices of a square frame [4]. To understand how the quadrotor operates, Newton's Third Law of Motion comes into play, stating that every action elicits an equal and opposite reaction [5]. When the quadrotor's motor rotates the propellers, it generates a downward force on the air, as explained by the Bernoulli Principle [6]. In a conventional quadrotor, adjusting motor speeds in the four motors allows the control of thrust and facilitates the required movements [7]. However, as the size and weight of the quadrotor increase, more thrust is needed to lift it, often necessitating larger propellers or faster motors, which in turn lead to higher power consumption and reduced flying time [8]. This conventional design approach can be both costly and inefficient [9].

Considering the issues of power consumption and cost, limited research has explored alternative methods to generate more thrust besides varying motor speed and propeller size [10]. One such study by Wu in 2018 proposed controlling the quadrotor through changes in both motor speed and rotor blade pitch angle, affecting the produced thrust and power consumption [11], [12]. Additionally, a simulation analysis in 'Effects of Variable Arm Length on UAV Control Systems' in 2020 highlighted the impact of varying arm lengths on the quadrotor's bending moment. Increasing the arm length resulted in higher bending moments and, consequently, increased thrust production [13]. To address these challenges and explore new possibilities, this project aims to design and test two concept designs for variable arms, ensuring smooth and stable extension and retraction.

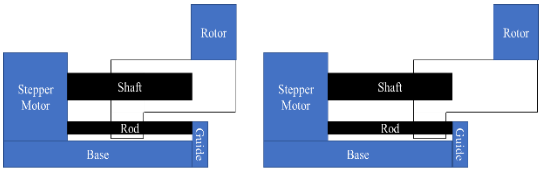
2. Design of variable arm

2.1. *Concept design*

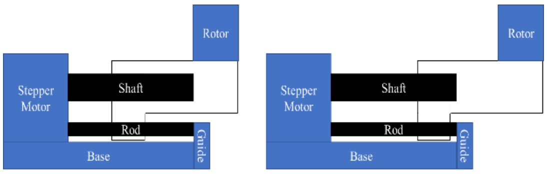
Fig. 1 shows three concept designs of variable arms in both the retract and extend positions. Fig. 1(a) corresponds to a concept design previously introduced in research [14]. However, when a quadrotor's arm experiences thrust, it may undergo deflection and vibration caused by the motor, impacting the arm's extension. To counter this issue, the use of a rod shaft and linear guide method for the variable arm proves effective in preventing arm deflection and ensuring smooth movement. The design depicted in Fig. 1(a) presents challenges in linear translation control due to the possibility of high deflection and the lack of motion guidance. On the other hand, the designs shown in Fig. 1(b) and Fig. 1(c) employ different methods for arm movement control. Fig. 1(b) employs a stepper motor with a screw shaft while Fig. 1(c) utilizes an electric actuator with a linear guide for variable arm control.



a. Variable arm concept



b. Variable arm of stepper motor with screw shaft and rod shaft (type 1)



c. Variable arm of electric actuator with linear guide (type 2)

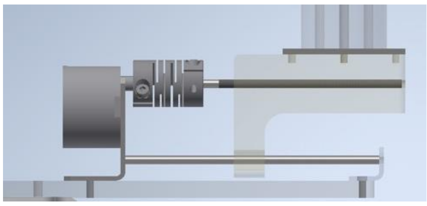
Fig. 1. Variable arm quadrotor design concept.

2.2. *Variable arm of speed motor with screw shaft and rod shaft (type 1)*

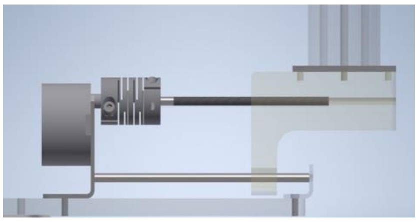
According to Eq. (1), the bending moment is determined by multiplying the force by the length. In conventional quadrotors, maneuverability relies on varying forces to influence the bending moment and consequently rotate the quadrotor's body. This means that the same force can produce different bending moments depending on the length of the variable arm. By manipulating the bending moment, the quadrotor can be directed and moved in a specific direction. For the purpose of testing, variable arms capable of moving within a range of 20 mm to 30 mm have been designed.

$$M = FL \qquad (1)$$

Fig. 2 illustrates the variable arm of type 1, utilizing a stepper motor with a screw shaft and rod shaft, in both the extend and retract positions. The 3D drawing is used to calculate the shaft's deflection using Eq. (2) and Fig. 3(a) assists in determining the moment of inertia. The results display the maximum deflection when the variable arm moves from its retracted position to a fully extended position, as depicted in Fig. 3(b).



a. Retract position



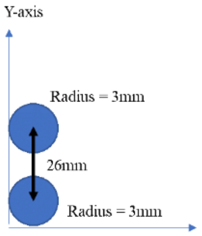
b. Extend position

Fig. 2. 3D modeling of variable arm steeper motor with screw shaft and rod shaft (type 1).

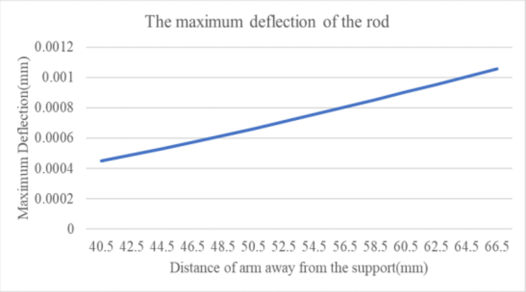
$$\delta_{max} = \frac{PL^3}{3EI} \qquad (2)$$

$$I_x = \frac{\pi r^4}{4} \qquad (3)$$

Analyzing Fig. 3(b), it becomes evident that the maximum deflection increases with an elongating length under a constant force. The maximum deflection amounts to approximately 0.001 mm, positioned 66.5 mm away from the support of the bracket design. Given its small magnitude, this deflection does not significantly impact the turning of the screw shaft caused by the deflection of the shaft.



a. Cross section of screws shaft and rod shaft



b. Maximum deflection of the shafts

Fig. 3. Deflection analysis.

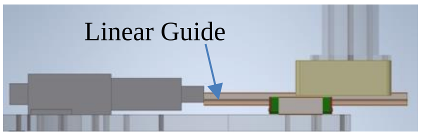
Furthermore, Table 1 presents the specifications of the stepper motor utilized, indicating an RPM range of approximately 15 to 20. With the use of a screw shaft of 0.5 mm pitch, the variable arm is able to move at the speed of 10 mm/min.

Table 1. The planning and control components.

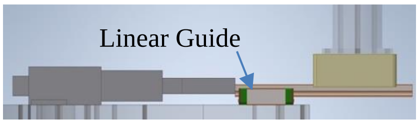
Technical Parameter	Value
Operating Voltage (V)	5
Operating Current (mA)	240
Step Angle	5.625/64
Reduction Ratio	1/64
Phase	4
Frequency (Hz)	100
Friction torque (gf.cm)	600-1200
Pull in torque (gf.cm)	300
Coil	Unipolar 5 lead coil
Decent Torque (mN.m)	34.3
Speed (RPM)	15-20

2.3. *Variable arm of electric actuator with linear guide (type 2)*

Fig. 4 presents the variable arm of type 2, which utilizes an electric actuator with a linear guide, in both the retracted position (Fig. 4a) and extended position (Fig. 4b). Referring to Table 2 reveals that the dynamic load of the linear guide is approximately 140 kgf. Considering the pull exerted by the brushless motor on the variable arm, it results in the moment of P acting on the linear guide.



a. Retract position



b. Extend position

Fig. 4. Variable arm of electric actuator with linear guide (type 2).

Table 2. Specification of MGN7H linear guide.

Technical Parameter	Value
Dynamic Load (kgf)	140
Static Load (kgf)	200
Moment of R (kgf.m)	0.78
Moment of P (kgf.m)	0.49
Moment of Y (kgf.m)	0.49

Given the small size of the 2 kg quadrotor, a force of 2 kgf is required to maintain equilibrium, while around 3 to 4 kgf thrust is needed to lift the quadrotor. In the design configuration, the center of the brushless motor is positioned 26 mm away from the center of the linear guide, enabling the calculation of the bending moment resulting from the thrust force applied to the linear guide, as per Eq. 1. The linear guide proves to be suitable for use, considering a maximum load of 4 kgf and a maximum bending moment of 0.104 kgf.m, leading to very minimal deflection of the linear guide.

Table 3 presents the specifications of the electric actuator used. As indicated in the table, the speed of the electric actuator is approximately 8 mm/s. Moreover, considering the force of 4 kgf, which equates to around 40 N, so the specification of the electric actuator is suitable for the variable arm application.

Table 3. Specification of LA-YR type electric actuator.

Technical Parameter	Value
Input Voltage (V)	12
No Load Speed (mm/s)	8
Load Push Capacity (N)	90
Load Pull Capacity (N) Static Damping (N)	90 90
Stroke Length (mm)	30

3. Testing on variable arms

Based on the concept designs presented in the previous section, two types of variable arms have been developed, as depicted in Fig. 5 and Fig. 6. The first type is variable arm of stepper motor with screw shaft and rod shaft referred to as type 1. It comprises a total of 11 components, including a motor driver to control the stepper motor, a bracket to secure the stepper motor, the stepper motor itself, a coupling to connect the stepper motor's shaft with the screw shaft, the screw shaft, a brushless motor, the variable arm, a bracket to hold the rod shaft, the rod shaft, a frame, and a linear bushing that ensures smooth movement of the variable arm along the rod shaft.

On the other hand, the second type, variable arm of electric actuator with linear guide known as type 2, is intended for an electric actuator with a linear guide. It consists of 6 parts: an MDD3A driver to control the electric actuator, the electric actuator, a linear guide, a frame, the variable arm, and a brushless motor.

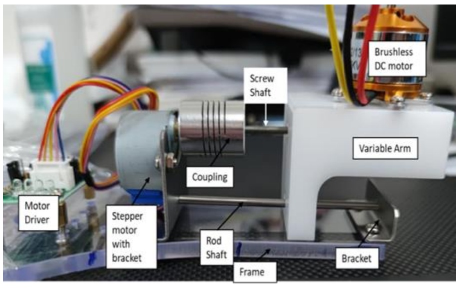


Fig. 5. Variable arm of stepper motor with screw shaft and rod shaft (type 1)

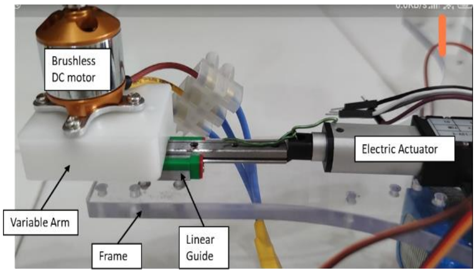
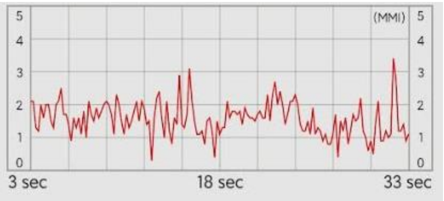


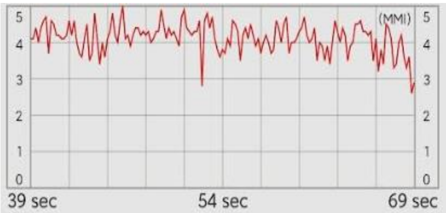
Fig. 6. Variable arm of electric actuator with linear guide (type 2)

Through the utilization of a mobile app equipped with a vibration meter, the vibration of the variable arm in motion is assessed. The phone is placed on the variable arm during the evaluation, and measurements are taken both with and without the operation of a brushless motor. The results are illustrated in Fig. 7 and Fig. 8, displaying the vibration levels with and without the motor's operation for both variable arms.

According to the graphs, it was evident that the brushless motor caused higher vibration, indicating that the motor generates significant vibrations. Additionally, a comparison between the two types of variable arms revealed that type 1 exhibited higher vibration than type 2.

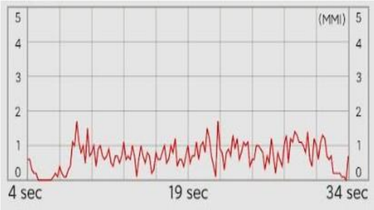


a. Without operation of brushless motor

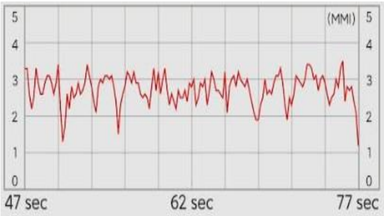


b. With operation of brushless motor

Fig. 7. Vibration data for variable arm of stepper motor with screw shaft and rod shaft (type 1)



a. Without operation of brushless motor



b. With operation of brushless motor

Fig. 8. Vibration data for variable arm of electric actuator with linear guide (type 2)

4. Conclusion

Table 4. Comparison between 2 designs – type 1 and type 2.

Design	type 1	type 2
Cost	Low	High
Weight (g)	139	96
Movement speed	Slow	Fast
Stability	High vibration	Low vibration

Based on the observations made during the motion of the two variable arms, the results presented in Table 4 indicate that using type 2 would be a more costly option. This is because electric actuators tend to be expensive when compared to stepper motors. However, it should be noted that the electric actuator demonstrated smooth and rapid movement, reaching approximately 8 mm/s, which made it well-suited for quadrotor control. Additionally, the electric actuator's advantage lies in its lightweight nature, as it utilizes fewer components, thereby minimizing the overall weight impact on the quadrotor.

Type 2 indeed offers a cost-effective solution. However, it comes with certain drawbacks. One major concern is the increased weight due to the presence of multiple brackets and shafts, which can adversely affect the overall performance of the system. Moreover, the movement of the variable arm driven by the stepper motor is not stable, mainly due to the high vibration experienced along the arm and its slow-moving speed. This instability can be attributed to the variable arm's elevated position, leading to a higher center of gravity, with the screw and rod shaft situated at the center of the variable arm. Consequently, this setup causes vibrations that oscillate the arm to the left and right. As a result, the thrust force provided by the brushless motor becomes unstable, impacting the system's overall performance.

Additionally, the pitch of the M3 screw shaft is merely 0.5 mm. As a consequence, with each revolution of the stepper motor, the variable arm can only move by 0.5 mm. This limited displacement capability results in the variable arm moving at a slow speed of only 10 mm/min, making it less suitable for certain applications that require faster movement.

In summary, type 2 is suitable to use as it provides fast motion and stability which is suitable for quadrotors that are sensitive to motion. Besides type 1, it will be suitable to use when a high-pitch screw shaft or higher RPM motor is used so that it can be moved faster. However, there is room for improvement in the design of type 1. One approach is to consider replacing the rod shaft with a linear guide or exploring other methods to enhance stability. Such modifications could help address the issues related to vibration and slow movement, making it a more suitable option for certain scenarios.

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Authors Introduction

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