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BLDC Motors: Optimal Propulsion for Multirotor Drones

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Abstract. Nowadays, drone technology is advancing, particularly in fields like agriculture and power inspection, and this has made efficient propulsion systems increasingly necessary. In the creation of multirotor drones, brushless current (BLDC) motors have become a crucial technology due to their numerous advantages over other types of motors, including stepping motors, permanent magnet-type synchronous motors, induction motors, and brush direct current motors. This paper analyzes BLDC motors' suitability for multirotor drones, describing their design and advantages. Because of its contactless design and FET inverter circuitry, which increases efficiency and results in longer flight times, the BLDC motor stands out in the drone industry. This paper also examines the potential benefits and present obstacles of BLDC motor technology, emphasizing the critical role that it plays in the development of aerial applications.

Keywords: component, BLDC motor, Aerial applications, Motor classification, FET circuits, Efficiency

1. Introduction

As a key component of contemporary technology, the motor industry demands a wide range of motor types since it needs to satisfy different operational requirements across different circumstances. Motors can be categorized into several types based on their working principles, such as stepper motors, brushless and brushed DC motors. Each kind of motor has unique benefits. Nevertheless, brushless direct current (BLDC) motors become the optimized motor choice because of their efficiency and precise control in applications such as robotics, electric vehicles, and, most importantly, multirotor drones.

A multirotor drone is a special unmanned helicopter with three or more rotors, widely utilized in industries such as agriculture and power inspection [1]. In detail, it collects information for precision farming and automates infrastructure inspections, which considerably lowers the risks and costs associated with performing tasks by human hands. But because multirotor drones have unique needs regarding the structure and function of their motors, specific design considerations need to be made, like these:

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1. Lightweight Design: Motors must have a lightweight overall design in order to be strong in terms of energy efficiency and load capacity [3].

2. High Power-to-Weight Ratio: The torque produced by a multirotor drone's motor needs to be adequate to match its weight [3].

3. Fast Response: In certain harsh weather conditions, motors in drones must maintain flight stability with quick responding ability to the pilot commands and auto adaptation component [3].

4. Minimal Maintenance: Motors for long-term drone use in some locations that are isolated or far-reaching should be stable and durable enough to minimize maintenance costs [3].

5. Noise Reduction: Motors should operate quietly so that the drones won't disturb activities such as animal monitoring [3].

BLDC motor is designed in four different components, including a control circuit, an inverter, a motor, and a position sensor (such as a Hall sensor [4]. Because of BLDC motors' superior design, the rotational speed and rotational torque could be precisely controlled. This would be important in many applications, for the requirement of smooth and steady efficiency. Further from multirotor drones, BLDC motors are also widely used in the civil UAV market, such as DJI camera drones and FPV (first-person view) drones [5]. They can fly for longer periods of time without maintenance compared with other motors. Even with all of their advantages, BLDC motors still have flaws, such as high cost and operating hazards from electromagnetic interference. There are still numerous issues that require attention to resolve and optimize.

In this paper, we will explore the components, applications, advantages, and limitations of various motor types classified by power supply (brushed DC motor, BLDC motor, AC motor, switched reluctance motor, stepping motor, ultrasonic motor). We primarily clarify the needs of the multirotor business and the benefits of BLDC motors. We also discuss the technical challenges regarding multirotor drones and the future of this field. Through the whole research, we aim to provide an overview of the motor industry, compare different types in the context of multirotor drones, and demonstrate possible methods for enhancing motor efficiency.

2. Background

An electric motor converts electrical energy into mechanical energy. Basically, Its operation is based on the electromagnetic induction theory, which is the attraction and repulsion between the coils and magnets [7]. The electromagnetic interaction between the rotor and stator generates the mechanical motion of a motor, regardless of its voltage source (DC or AC). In this section, We will introduce the stator and rotor, which are fundamental parts of every motor, and some most used types of motors.

The stator, mostly made up of windings and an iron core is a stationary component of a motor. It helps to create a magnetic field in both DC and AC motors. The stator of brushed DC motors is often made up of electromagnetic coils or stationary permanent magnets. On the other hand, in a BLDC motor, the stator is made up of several phase windings (distributed electromagnetic coils) around the circumference [6].

The rotor, sometimes called the armature, is the rotating part of the motor, located inside the stator. The function of the rotor is to generate mechanical motion in the magnetic field of the stator. In a brushed DC motor, the rotor (also known as the armature) is composed of one or more windings. In brushless DC motor, the rotor of a brushless DC motor is usually composed of permanent magnets [6]. The various types of motors are all modified based on these two components. With different usage, they have disparate structures, resulting in completely diverse advantages and disadvantages

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2.1. Brushed DC motor

Brushed DC (BDC) motors actually get their name from the carbon brushes, electrodes that conduct current to the armature windings (the rotor) by maintaining contact with the commutator. Then, the commutator, a segmented copper device, mechanically reverses the current flow through the armature windings. This in turn changes the magnetic field direction to enable continuous rotation [8].

In terms of the motor's working principle, Brushed DC motors have a rotor with wound coils and a stator generating a magnetic field. The two ends of the coil are connected to the commutator. When DC power is supplied, an electromagnet is formed as long as it remains in contact with the brushes. According to Fleming's Left Hand Rule, a magnetic force causes the rotor to rotate. As the coil rotates, it reaches a position where the brushes lose contact with the segments of the commutator, interrupting the current flowing in the coil, and causing the poles of the electromagnet to reverse. This entire process generates a continuous repulsive force, allowing the coil to keep rotating [9].

Brushed DC motors can be classified into 3 groups with different applications based on the structures of their stators.

2.1.1. Permanent Magnet DC motor

The permanent magnet DC (PMDC) motor uses a permanent magnet to produce the magnetic field. As shown in Fig. 1 Its stator is constituted by a steel cylinder with multiple magnets arranged along the inner perimeter. Their North (N) and South (S) poles face the armature in an alternating structure [3]. These motors are commonly used in models, automotive auxiliary devices, and various other applications.

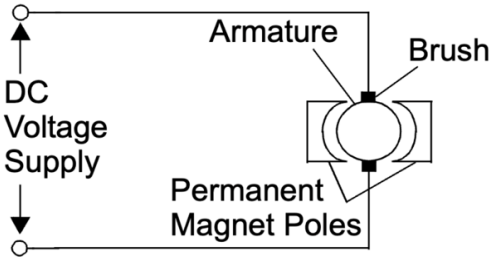


Figure 1. Construction of permanent magnet DC motor

2.1.2. Self-cited DC motor

A self-excited motor is a type of DC motor where the current in the windings is supplied by the motor itself. There are three types: shunt-wound, series-wound, and compound-wound motors.

Shunt-wound motors have the field winding connected in parallel with the armature winding, providing a steady magnetic field. They are used in applications requiring consistent speed, such as lifts and fans.

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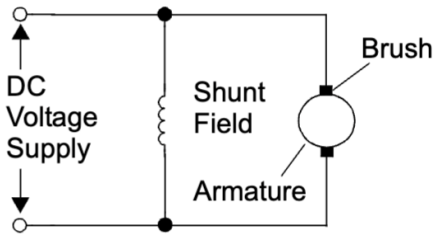


Figure 2. Construction of shunt-wound motor

Series-wound motors pass electrical current through both the armature and field coils connected in series, causing torque to start quickly and variably. They are well suited for applications where speed regulation is very critical.

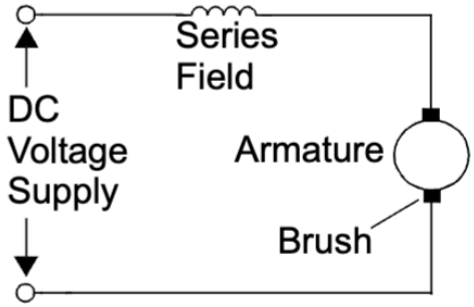


Figure 3. Construction of series-wound motor

Compound-wound motors combine features of series and shunt-wound motors. So, it provides both strong starting performance and consistent speed regulation under varying loads. They are commonly used in applications where reliable operation across different conditions is essential.

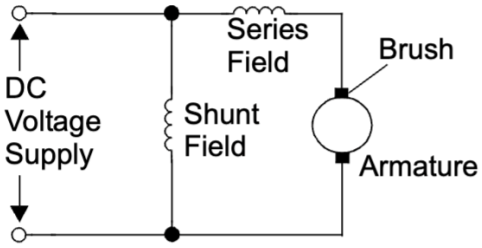


Figure 4. Construction of compound-wound motor

2.1.3. Separately-excited DC motor

A separately excited DC motor is a DC shunt wound motor but with a dissimilar power source arrangement. This motor is different from other types of DC motors in that it uses separate DC voltage sources for both the armature and field coils. The said motor uses constant DC voltage to power the field coils and can be fed with an armature voltage that can be varied. This spacing provides electrical isolation between the coils and allows operation of the motor above base speed within the field-weakening region by decreasing the field current and reverse rotation by adjusting the armature voltage.

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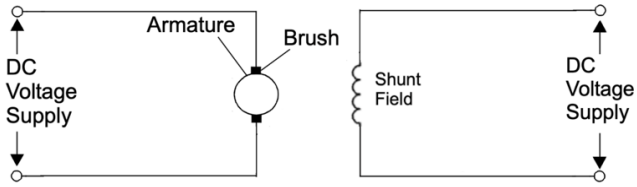


Figure 5. Construction of separately-excited DC motor

2.2. Brushless DC motor

To begin with, most of BLDC's structures are like brushed DC motors, including permanent magnets, complicated coils, and other electronic components. However, unlike brushed motors, BLDC motors eliminate the use of carbon brush which significantly reduces the energy loss and thermal friction in the motors. Therefore, BLDC motors usually have a higher RPM (revolutions per minute) limitation, resulting in higher working efficiency compared to the other motors.

With the application of a brushed motor, rotation is achieved by controlling the magnetic fields generated by the coils on the rotor. Meanwhile, the magnetic field generated by the stationary magnets remains fixed. In order to change the rotation speed, users need to change the voltage for the coils. In a BLDC motor, however, it has permanent magnets to allow it to turn. Unlike the brush DC motors, where the rotation is achieved by the reversal of the magnetic field's direction, which the surrounding coils create, and those are immobile

Contrary to the mechanical commutation of other motors, BLDC motors use electronic commutation as a working principle. The key components of a BLDC motor include a stationary stator and a permanent magnetic rotor. The stator contains several coils of wire wound around iron cores and it's usually arranged in a three-phase configuration. When electric current flows through these coils, they generate a magnetic field that interacts with the magnetic field produced by permanent magnets in rotors.

The operation of the BLDC motors is based on the precise control of the current flow in stator windings. Electronic commutation makes it possible to change the direction of current flow accordingly in an order that corresponds to the position of the rotors. In BDC motors, physical components are used to change the direction of current flow. In BLDC motors, however, they use semiconductor switches—most often MOSFETs or IGBTs—for electronic switching.

The rotor position and rotor speed define the switching sequence. In this regard, magnetic poles can be sensed by Hall effect sensors mounted inside the motor when the rotor magnet passes by, hence being able to offer real-time feedback to the motor controller. The sensorless techniques are based on the algorithm that estimates rotor position from the back electromotive force (EMF) induced in the stator windings.

The motor controller can produce a rotating magnetic field by properly controlling the current turn-on and turn-off in the stator windings; hence, it is capable of exerting force on the rotor’s permanent magnets to rotate it. Hence, precise control of the speed and torque output of the motor can be gained.

Some of the advantages of BLDC motors over BDC motors are much more. First, they have higher efficiency due to reduced energy losses by friction and brush contact resistance. Second, it requires fewer maintenance needs because there are no carbon brushes. It also makes the system more reliable since solid-state electronic components are much more rugged. Their application in a wide variety of different industries is possible because of their accurate speed control, high efficiency, and reliability. Examples of these are the automotive systems—electric vehicles and

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hybrid vehicles, aerospace applications—drones and UAVs, industrial machinery—robots and automation equipment, consumer electronics—household appliances and power tools.

2.3. AC motor

In AC motors, electric current is reversed periodically to make AC motors function, the rotary motion is caused by reciprocating electric current flowing. An AC motor consists of a stationary stator and a rotating rotor. When AC power is applied, interactions between the stator's and the rotor's magnetic field occur. Then the whole mechanical system begins to work.

An alternator is an essential device for AC motors, its function is to produce alternating current. An alternator is a unique kind of electric power generator that works by rotating a shaft, or rotor, in or around a set of stationary coils, or stator, to produce an electromagnetic field (EMF). As the rotor rotates in relation to the stator, this electromagnetic field (EMF) shifts in direction or polarity, providing the AC motor with the force necessary to convert electrical energy into mechanical energy efficiently.

AC motors are divided into synchronous and asynchronous motors based on their rotational speed in respect to the stator magnetic field's rotational speed (synchronous speed). Asynchronous motors rotate at a speed that is less than that of the stator magnetic field, whereas synchronous motors rotate at the same speed as the stator magnetic field.

2.3.1. Synchronous motor

Synchronous motors are operated by synchronizing the rotating magnetic field generated by the stator with that of the rotor, which usually consists of permanent magnets or electromagnets with excitation windings, as shown in Fig.6. Startingly, the rotor is gradually accelerated and eventually synchronized with the rotating magnetic field of the stator for the purpose of maintaining a constant speed. The main characteristic of a synchronous motor is that the speed is proportional to the power supply frequency, enabling it to maintain a constant speed as the load varies. In addition, the power factor of the motor can be effectively controlled by adjusting the rotor excitation current, so that efficient operation can be maintained under different working conditions. Because synchronous motors have the characteristic of stable speed and good power factor control capability, they are often used in applications that require precise speed control, like clocks and some other high-precision timing equipment.

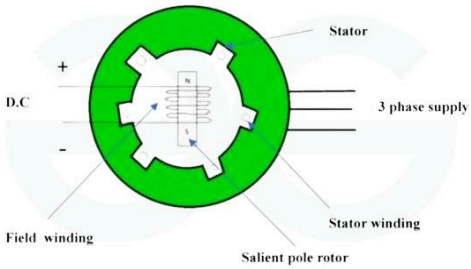


Figure 6. Construction of synchronous motor

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2.3.2. Asynchronous (induction) motor

Just as with the other motors, electromagnetic induction is used to interact with magnetic fields from the asynchronous motor's stator, the rotor rotates due to the induced current in it. To make sure the motor runs steadily, there is always a certain rotational speed difference kept between the rotor and the stator magnetic field.

Because of their straightforward design and low cost, asynchronous motors can be found in several industrial equipment.

2.4. Stepping motor

An electric motor that rotates in tiny angular increments without the aid of a position sensor is called a stepping motor. It is made up of a stator and a rotor, where the rotor can be an iron core with variable resistance or a permanent magnet. Coils are wired onto the stator's teeth, and as current passes through them, a magnetic field is created that pushes the rotor into alignment with the field.

Stepping motors come in different types based on their rotor construction: variable reluctance (Fig.7), permanent magnet (Fig.8), and hybrid (Fig.9). These types have different advantages and applications. Variable reluctance motors achieve higher speeds and resolutions more easily but often produce lower torque. Permanent magnet motors guarantee good torque and detent torque, resisting a change in position, but are slower and have lower resolution. Hybrid motors combine the advantages of both types, offering high resolution, speed, and torque but are more complex and costly to construct.

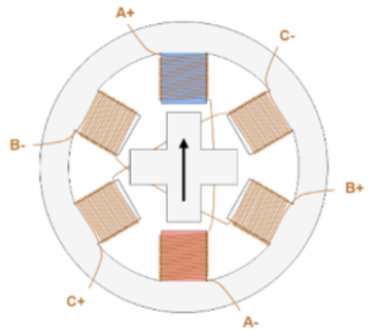


Figure 7. Construction of variable reluctance stepping motor

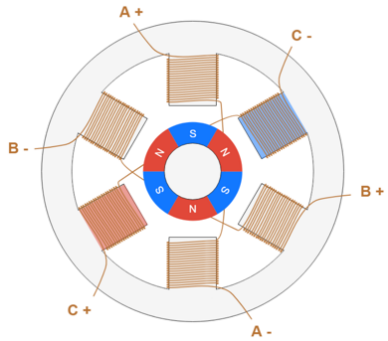


Figure 8. Construction of permanent magnet stepping motor

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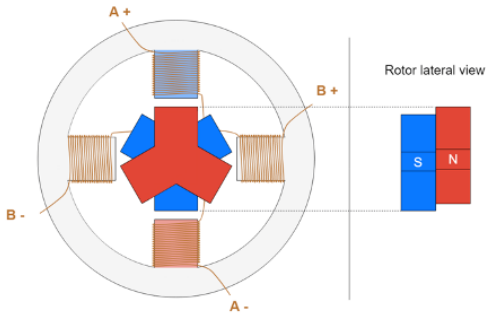


Figure 9. Construction of hybrid stepping motor

Bipolar driving circuits, which employ MOSFETs to regulate the current direction in the coils, are used to control the movement of the motor. As a result, the motor can produce the highest torque possible given the quantity of copper used. Stepper motors are frequently found in high-accuracy machinery like printers, DSLR cameras, and other gadgets.

In conclusion, stepper motors eliminate the need for external position feedback by offering precise control over the motor shaft's rotation. Because they can hold positions and transition quickly to new ones, they find use in a variety of fields. The performance characteristics of the motor are determined by the type of rotor construction, and the movement of the motor can be controlled by a variety of driving circuits.

2.5. Ultrasonic motor

The rotation of most of the traditional electric motors is based on the electromagnetic repulsive force between the stator and rotor. So if the motor is placed in an environment with high voltage or electromagnetic interference, it may be strongly affected and function falsely. However, in some special fields, the interference by magnetic fields cannot be avoided. Besides, there are some other fields which need motor with volume as micro as possible. Due to these two main reasons, a motor with a brand new structure is invented: Ultrasonic motors (USMs).

The principle of how the rotor rotates in a USM is completely different from all others (in Fig.10). The most significant difference is that it does not need an electromagnetic field to carry out the rotation. The part of the stator that contacts with rotor is made of piezoelectric ceramics. Ultrasonic motors use the inverse piezoelectric effect of piezoelectric ceramics to convert electrical energy into mechanical energy and cause vibration. Instead of using coils or magnets to generate rotational energy, this special material can deform when a voltage is applied, and inversely, recover when the voltage is removed. The deformation of it is amplified and controlled by a stator to stretch and recover back and forth at a specific frequency（usually 20~100kHz）, thus the ends of these piezoelectric ceramics are able to have a rotating motion with an oval shape. This rotational motion is transmitted to the rotor, which presses against the stator, causing the rotor to rotate using the act of friction. A shaft is fixed to the rotor and transmits the torque and rotation of the motor outwards. Since this friction continuously occurs between the piezoelectric ceramics and the rotor, the position of the shaft can be maintained even when the motor is powered off and out of control.

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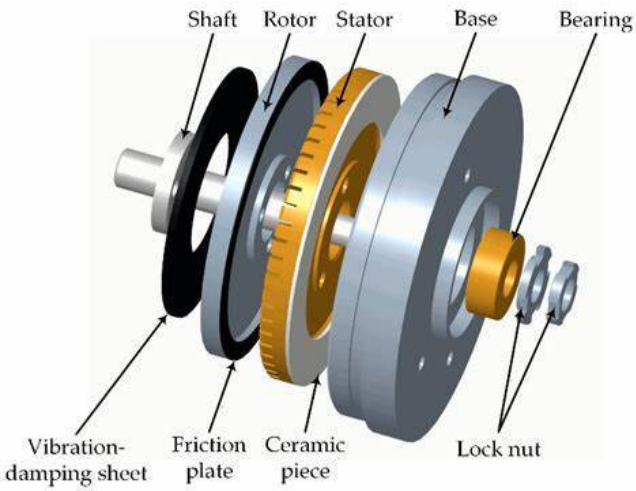


Figure 10. Construction of ultrasonic motor

2.6. Switched reluctance motor

Following the development of DC and BLDC motors, switched reluctance motors (SRM) are a class of speed-regulating motors. Its special construction makes effective use of the electromagnetic field by avoiding a direct electrical connection to the rotor. The stationary stator and rotor that make up the SRM are distinguished by their salient pole designs. The magnetic flux distribution inside the motor is controlled by the stator, which consists of a laminated silicon steel core with windings around several salient poles that are energized in a particular sequential order via electronic switches. As to the difference between an SRM and other motors, the rotor of an SRM consists of ferromagnetic material without windings. Thus, the result will be one with fewer prominent poles as compared to the stator. Different phase numbers can be applied as well as combinations of the rotor and stator pole of an SRM. In modern times, a six-phase (12/8) and four-phase (8/6) structure are used more frequently than others. The operation of an SRM follows a 'minimum reluctance principle.' This principle contends that magnetic flux always closes along the path of least reluctance, aligning with the energized stator poles, which in effect reduces magnetic reluctance. A control circuit regulates the switching of the stator windings with respect to the rotor position so that torque generation and efficiency can be maximized at different operating speeds. The structural simplicity of SRMs makes them durable and, therefore suited when quick changes in torque and speed occur. This, therefore, makes the SRM dependable and efficient, offering the industry an alternative to its reputable functioning—especially the automotive and industrial industries.

Table 1. Comparison of different motor types

Motor Type	Brief Structure	Advantages	Limitations	Applications
Brushed DC motor	Stator: Permanent magnets or electromagnetic coils, commutator, Armature windings	Simple constructure, Easy control of speed and torque, Low cost	Brushes and commutator wear out overtime, High maintenance requirements	Automotive auxiliary devices, Models, Industrial machinery
Brushless DC Motor	Stator: Electromagnetic coils, Rotor: Permanent magnets	High efficiency, Low maintenance, Precise speed and torque control	More complex electronic control system required, Higher initial cost	Electric vehicles, Hybrid vehicles, Drones, Robotics, Power tools

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Table 1. (continued)

AC Motor	Stator: Stationary coilsRotor: Permanent magnets or iron core with variable reluctance	Simple constructure, Low cost, High power output	Lower efficiency compared to DC motors, Less precise speed control	Household appliances, Industrial machinery, HVAC systems, Electric vehicles
Stepping Motor	Stator: Teeth with wired coils, Rotor: Permanent magnet or iron core with variable reluctance	Precise position control, No need for position sensor, Rapid movement between steps	Low torque output, Lower efficiency compared to other motors, Higher cost	Printers, DSLR cameras, Robotics, Automation equipment
Ultrasonic Motor	Stator: Piezoelectric ceramics Rotor: Ferromagnetic material	No electromagnetic interference, Compact size, High torque at low speeds	Limited speed and load capacity, Complex control circuitry, Higher cost	Cameras, Precision equipment, Robotics, Medical devices
Switched Reluctance Motor	Stator: Salient poles with windingsRotor: Ferromagnetic material	Simple structure, High durability, High speed operation	Vibration and noise during operation, Requires precise control of stator winding switching	Industrial machinery, Automotive systems, HVAC systems, Electric vehicles

3. Brushless DC motors' applications in the drone industry

Multirotor unmanned aerial vehicle (UAV) uses more than two rotors with fixed-pitch rotating blades to produce lift. Unlike in a helicopter, the rotor's angle is fixed rather than adjustable. This design significantly influences the application of this type of drone. Some typical multirotor UAVs, including octocopters, hexacopters, and quadcopters, are renowned for their high mission completeness probability in performing tasks.

The multirotor is relatively simple and stable. The appearance of the multirotor aircraft implemented at present is much smaller than that of aircraft, so it is suitable for industry working and leisure use. The multirotor drone is simple to operate and can take off and land vertically without a runway. The multirotor drone's reliability depends on the brushless motors, so it has higher reliability. At the same time, multirotor UAVs with easy operation and strong stability have been widely used in many industrial and agricultural fields.

In the agricultural field, farmers are able to learn to operate multirotor drones quickly, and the drones can also carry various payload types, such as liquid pesticides or seeds. So, it is very effective for spraying and seeding. In industry, UAVs are used for mapping in mining and surveillance.

3.1. Five basic types of multirotor drones

3.1.1. Trirotor

The Trirotor, as its name suggests, is made of three rotors to generate buoyancy and is used for movement and control. And the arm distance is usually 120 degrees, at the meantime, it is typically in a "Y" shape or in a "T" shape. The advantages of a trirotor drone are its light size, low cost, and flexibility, as it only requires three rotors, which is a relatively inexpensive configuration. At the same time, it also has lower lifting power because of the motor numbers.

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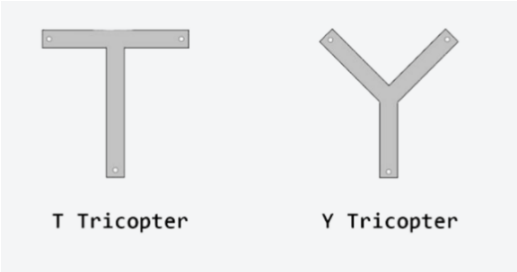


Figure 11. Construction of trirotor

3.1.2. Quadrotor

Quadcopters are a common type of multirotor the most popular being the "X " and "H" shapes. Four motors are mounted on a symmetrical frame, and each arm is usually 90 degrees apart in an X4 configuration. Two of the motors rotate CW (clockwise) and the other two rotate CCW(counterclockwise) to generate opposite forces to keep balance. It achieves perfect performance for price, stability, and flight time.

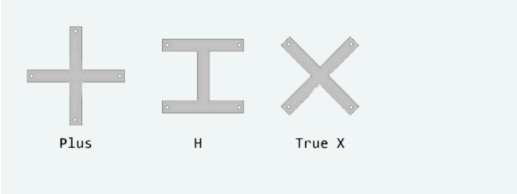


Figure 12. Construction of quadrotor

3.1.3. Hexacopter

The hexacore is mounted on a symmetrical frame, and each arm is usually 60 degrees. Compared to the quadrotor, the hexacopter has more motors to increase power and stability. Meantime, it also improves redundancy so that even if a motor fails during flight, it can still work properly in the air and land safely. However, motors will have more power consumption, so the flight time will be reduced. It is also similar to a quadcopter, three motors rotate CW (clockwise) and the other three rotate CCW (counterclockwise) to generate opposite forces to keep balance.



Figure 13. Construction of hexacopter

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3.1.4. Octocopter

The octocopter usually has eight rotors, so it has strong stability and power, which is able to take greater payload and has stronger wind resistance. It looks more like an upgraded quadrotor and hexacopter. Octocopters are often used for film or professional purposes which can be mounted with heavier cameras and lenses. But because of the increase in the number of motors, its energy consumption is fast and the drone frame size is large.

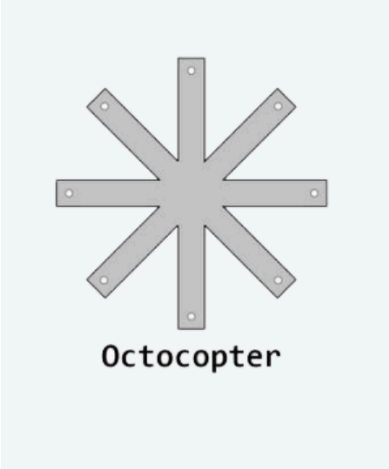


Figure 14. Construction of octocopter

3.1.5. Coaxial multirotor drones

There is also a special type of multirotor drone named coaxial multirotor UAV. Coaxial rotors are a pair of rotors mounted on concentric axes, having the same axis of rotation but turning in opposite directions. For example, the typical coaxial octocopter is also known as a coaxial X8 drone, which uses 8 motors mounted on 4 arms and it's an upgraded quadrotor with more power and less space. Our product MX860 adopts the coaxial X8 drone frame, which greatly reflects the features of small in size and large payload.

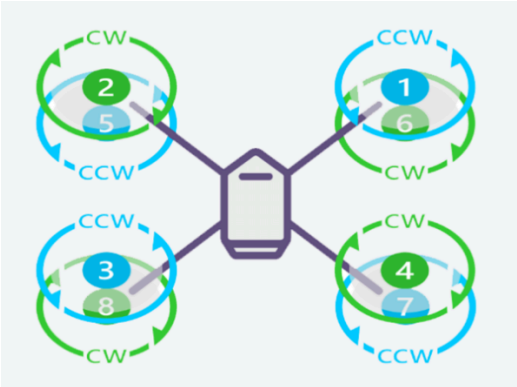


Figure 15. Construction of coaxial multirotor drones

The use of multirotor drones can vary significantly depending on the circumstances. The type of motor used for the propulsion system is the most important component for their application. Nowadays, BLDC motors are well suited for the distinct requirements of this part. However, the

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reasons for their high suitability in the context of multirotor drones may not be immediately apparent.

3.2. BDC motor

Brushed DC motors (BDCMs) have several unique characteristics that set them apart from other types of motors, such as brushless DC motors (BLDCMs), in the drone industry. Here are some unique characteristics:

3.2.1. Simplicities

BDC motors are mechanically simple and cheaper to manufacture. Therefore, these characteristics make them an attractive option for low-level drones. Besides, their simplicity in structure also makes them easier to control. In contrast, other motors are often more complex and expensive. This is mainly because of the need for electronic communication and advanced control circuitry; thus, the total cost of making a UAV is high.

3.2.2. Ease of control

BDC motors are easy to control since they only rely on a simple switch and basic ESC for speed regulation. The change in motor speed is directly proportional to the applied voltage, making them user-friendly for beginners or hobbyists. Conversely, other motors such as BLDC motors, always require more sophisticated ESCs that use pulse-width modulation (PWM) or other advanced methods for speed control, which can be more challenging for beginners.

3.2.3. Reliability and maintenance

One of the weaknesses of BDC motors is the presence of carbon brushes and a commutator. These make them need frequent maintenance. Additionally, the abrasion will reduce the motor life. Reversely, the BLDC motor has a longer life which is mainly because of the absence of carbon brushes. This makes them more reliable and less maintenance requirements.

3.2.4. Efficiency and power-to-weight ratio

BDC motors generally have lower efficiency compared to BLDC motors because of a significant amount of energy losses. Their low power-to-weight ratio is a disadvantage in high-performance drones. In contrast, BLDC motors are more efficient in energy transformation. Moreover, it possesses a higher power-to-weight ratio. This makes them suitable for applications when there is a high requirement for payload capacity.

3.3. AC motor

AC motors are less used in the drone industry compared to DC motors, especially brushless DC motors (BLDCMs). However, they have some unique characteristics which make them suitable for certain situations. The content below is a comparison between AC motors and other motors:

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3.3.1. High efficiency at constant speeds

AC motors are renowned for their effectiveness during the working process. They are advantageous for a variety of applications because they can continue to operate under varying extreme conditions. Likewise, BLDC motors are very efficient, but they are typically more appropriate for applications that need variable speed control instead of an environment that is too harsh.

3.3.2. Durability and longevity

The durability and longevity of AC motors are important. This is because they have fewer moving parts compared to BDC motors. Besides, it also helps AC motors reduce abrasion; thus, they can sustain for a longer operational time. However, AC motors sometimes need frequent maintenance because of harsh working conditions.

3.3.3. Robustness and reliability

AC motors are robust and perform very well even under severe environmental conditions. They are less sensitive to variations in loads and can cope with higher power levels. Although BLDC motors also have high reliability and durability, AC motors could be probably more reliable in harsh environments. The robustness is a major reason why AC motors have this broad industrial application.

3.3.4. Complexity and control requirements

AC motors need more complex control systems for variable-speed applications compared to other motors. AC motors are weak in the situation where variable speed regulation is needed. In contrast, BLDC motors are easier to control and cheaper, making them a better choice for drone applications.

3.4. Stepping motor

Stepper motors differ from other drone motors, such as brushed DCs, BLDCMs, or AC motors, in a few unique features. Niche applications and special characteristics make them different from all other motors. Here are some of their unique characteristics:

3.4.1. Precise positioning and control

Their main advantage is the ability to move in discrete steps—hence, stepper motors—enabling a lot of control over angular position with no need for feedback systems like encoders. That makes them useful where accurate positioning is required, such as camera gimbals and sensor alignment systems. Most of the other motors, such as BLDCs, require additional sensors in the form of encoders or Hall sensors to give this type of position accuracy. While BLDCs are excellent in terms of speed and torque control, they inherently do not offer the same level of precise open-loop position control as that of stepper motors.

3.4.2. High holding torque

In fact, stepper motors can hold torque at their position even when powered off because they have high holding torque without the consumption of power or complex control systems. This particular characteristic proves very helpful in cases where the motor needs to hold a load in one position, such

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as a stabilization system or in payload position control. However, BLDC and other types of motors generally need active feedback or constant power to hold their position and may not exhibit the same holding torque without considering further control systems.

3.4.3. Simplicity for control in positioning tasks

The stepping motors are rather easy to control regarding their positioning tasks since they can be directly driven from pulse signals corresponding to each step. Thus, many applications do not need a hard implementation of motor control algorithms and feedback. Although BLDC motors offer better performance in speed and power characteristics, it is usually done at the cost of more complex electronic speed controllers (ESCs) and feedback systems, which again increases the system complexity.

3.4.4. Repeatability and accuracy

Due to their ability to move in fixed steps, stepper motors offer excellent repeatability, meaning they can return to the same position consistently after repeated movements. This is essential in applications where accuracy is more critical than speed, such as in LIDAR systems or robotic arms on drones. Reversely, other motors may require additional calibration and feedback to achieve similar repeatability and accuracy, especially when dealing with complex or variable loads.

3.5. Ultrasonic motor

3.5.1. Small size

The piezoelectric ceramics on the stator can be made short in length, and the rotor is simply a metal (or other material) lamina, which keeps the motor small. As a result, USMs are extensively used in the micromechanical technology industry where compact size is essential. In the medical field, USMs have been successfully applied to surgical robots and other surgical instruments.

3.5.2. Rotates with low speed

It is the vibration of the piezoelectric ceramics that causes the rotor to rotate. When voltage is applied and removed from the piezoelectric ceramics at a specific rate, they vibrate in an oval shape with a frequency typically between 20 and 100 kHz, similar to each piezoelectric ceramic rotating. The rotor, which contacts the ceramics, moves due to friction. Because the piezoelectric ceramics are micro-sized, the radius of each rotation is small, resulting in a slow rotation speed of the rotor.

3.5.3. High torque

A large amount of piezoelectric ceramics is used on the stator of the motor. On vibrating, they (rotating) apply a small amount of friction to the rotor. Although not a large force from each individual ceramic, the total force acting on the rotor will be tremendous. Because of this, USMs can produce higher torque than any other kind of motor.

3.5.4. High rotation accuracy

Because of the presence of the piezoelectric ceramics between it and the rotor, the rotor can only stop immediately upon removal of the voltage as it rotates by friction. At this point in time, the static

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friction force is large, holding a large torque, thus providing a large start-stop control from the macro point of view.

3.6. Switched reluctance motor

The switched reluctance motor is a type of DC motor that uses the switched reluctance effect. It has the characteristics of simple structure, large torque, and fast response speed; meanwhile, it finds great wide usage in modern industry. The following will illustrate the difference between the SRM and the BLDC motor.

3.6.1. High torque

A switched reluctance motor has a usually more powerful torque than a BLDC motor of similar power because it can use alterations in the electromagnetic field to create a higher driving force.

3.6.2. Fast response speed

The response speed of the switched reluctance motor is usually fast because its working principle determines that it can respond to the control signal faster.

3.6.3. Strong controllability

Speed and torque control can therefore be accurately executed in switched reluctance motors through changes in reluctance angle.

To sum up, the advantage of a switched reluctance motor is that the structure is simple and the control circuit is relatively simple, which suits some low-power and low-speed applications. Some of the advantages of a brushless motor include high efficiency, high speed, high power, and low noise; hence, it can suit some high-performance applications.

3.7. The advantages of BLDC motors in this unique structure

3.7.1. Power density and efficiency

High power density is important for drones, as they generally require the characteristic of high-energy transformation efficiency. This is therefore able to assure the efficiency of the overall system. BLDC motors have much higher energy transformation efficiency compared to traditional brushed motors. Moreover, energy loss is drastically reduced in BLDC motors because they are brushless motors. In addition, BLDC motors have better speed versus torque characteristics [13].

3.7.2. Fast response

In the flight control of a UAV, the fast response capability is critical. Fast response-ability can help UAVs achieve precise attitude control and stable flight performance. This requirement is particularly important because the UAV needs to make frequent adjustments. As a result, motors must have good dynamic response to provide the required torque and speed changes in a moment.

BLDC motors demonstrate significant advantages in terms of fast response. Because BLDC motors are driven by electronic controllers, the speed and torque of the motor can be precisely controlled. This precise control capability enables the BLDC motor to provide extremely high

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dynamic response speeds. As a result, BLDC motors perform well in UAV applications, especially in scenarios with high dynamic requirements.

3.7.3. Low noise and vibration

Low noise and vibration are key requirements in the design of UAVs. These two things might not only interfere with the precise equipment on UAVs but also increase the risk of detection. Therefore, motors need to possess the characteristics of low noise and vibration to ensure stealth and stability.

In brushless DC motors, their brushless design reduces internal mechanical friction, which significantly reduces noise and vibration during operation. Compared to traditional brushed motors, BLDC motors have no physical contact between the brushes and the commutator, which means that there is no noise from worn brushes during operation and no increase in vibration due to friction. ‘Because the windings remain stationary, no potentially troublesome moving electrical contacts, i.e., brushes are required. In addition, stationary windings are easier to keep cool.’ [14] This design not only eliminates brush wear and associated noise but also reduces vibration due to mechanical friction. All of these features make BLDC motors particularly suitable for use in UAS applications where low noise and vibration are critical.

3.7.4. Durability and reliability

Motors operating in UAVs always face a range of extreme weather conditions, including heavy fog, hailstone, and fluctuations in temperature. The motors' performance can be greatly affected by these harsh environments. As a result, the chosen motor needs to be exceptionally durable to guarantee steady performance over extended periods of use under such circumstances.

In fact, BLDC motors are renowned for their durability. First of all, because BLDC motors are brushless, there is no surface contact with one another. So, there would be no friction between brush wear and tear, which significantly extends the life of the motors. Furthermore, BLDC motors can function steadily in extremely hot environments because they are typically constructed with premium materials with great adaptability and unique but sophisticated techniques. As a result, BLDC motors are especially well-suited for use in multirotor drones because of their performance in harsh environments.

4. Advancements and future directions for BLDC motor applications

It is true that the BLDC motor is popular in UAVs, but it's not perfect actually. There's still a lot of research to be done and many improvements to be made to increase both its efficiency and performance. For example, the ESC plays a key role in controlling the operation of BLDC motors. So ensuring optimal compatibility between the ESC and the motor has become essential. Mismatches can cause issues such as overheating, inefficiency, or even damage to the motor.

4.1. Home appliances

BLDC motor is used in a large number of areas, and domestic shares a large proportion of it. Many factories choose to use BLDC in powerful electric appliances such as air conditioners. The main reason is its reliability. These electric appliances need to be durable so that they can be used for a long time without breaking or the need of maintenance. But the other factor that needs to be considered to make BLDC motors more suitable at home is efficiency. BLDC motors in powerful electric appliances take a large amount of electricity, which raises electricity bills. So, the efficiency

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of BLDC motors needs a breakthrough, to decrease the electricity need for the same power in order to save money. One of the ways to improve motor efficiency is to replace traditional methods with soft magnetic composite materials (SMC) or iron powder materials, this is a future development direction.

4.2. Vehicles

The auto industry is another industry where BLDC motors are widely used. Electric cars have become very popular in recent years. As the BLDC motor has a relatively long life span, it can run properly on an electric car for a quite long time. This characteristic ensures the safety of electric car driving. BLDC motor has some other benefits, like high torque， high rotation speed, and low maintenance cost. All these reasons lead to the use of BLDC motors in many types of electric cars. To make the vehicles have better performance, BLDC motors should be improved to have higher power density and efficiency, reduced size and weight. So, motor companies need to adjust the ratio of BLDC motor's diameter and height, to find the best ratio which guarantees both torque and economic efficiency for vehicles.

Cooling for the motor is also a problem. During the operation of the motor, heat will be generated due to the current passing through the winding and the iron core, resulting in an increase in the temperature of the motor. If the motor temperature is too high, it will affect the performance and life of the motor, and may even cause safety accidents. Therefore, the heating and cooling problems of the motor need to be effectively controlled. The heating of the motor is mainly caused by the resistance loss and magnetic core loss caused by the current in the winding and the iron core. Using aerodynamics to move air through the motor is the most common way. A more efficient aerodynamic profile is essential to lead the airflow through to cool the motor, which is worth studying in the future.

4.3. Aerospace

Considering the use environment of aircraft spacecraft, the physical location of brushless motors in aircraft systems, usually located in extreme environments like the extreme cold at 10,000 meters, requires maximum and strongest performance in the required motor frame size.

One of the design considerations for motors is the material. The selection of magnet material should ensure that the strength of the frame will not decrease with the change in temperature. So, the engineers need to keep doing some experiments to find a stronger alloy that won't be affected easily by temperature change so that the motor can have a better performance in these extreme environments.

Material for the magnet should also be considered. A magnet that has better performance to withstand these extreme working environments and keep it magnetic needs to be invented.

5. Conclusion

In conclusion, BLDC motors are preferred for multi-rotor drones because of their distinct advantages in performance, efficiency, and control. Advanced electronic commutation and a structure without contacts stop wear and tear and cause minimal losses; thus, there is high power output with extended operation lifetimes, and the motors require less maintenance. BLDC motors also provide characteristics of Accurate control of torque and speed. Make them widely used in areas such as aerial cinematography, logistics, and surveillance. However, this is considered a large issue:

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expenses and technological constraints. Such challenges can never be so major that they will restrict the integration process in drone ecosystems, especially when future research on these issues unfolds. This will only act as an impetus to the process of functional innovation and innovation in the user experience. Eventually, it is the advanced propulsion system and the role played by BLDC motors in this regard which is advancing the drone technology.

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