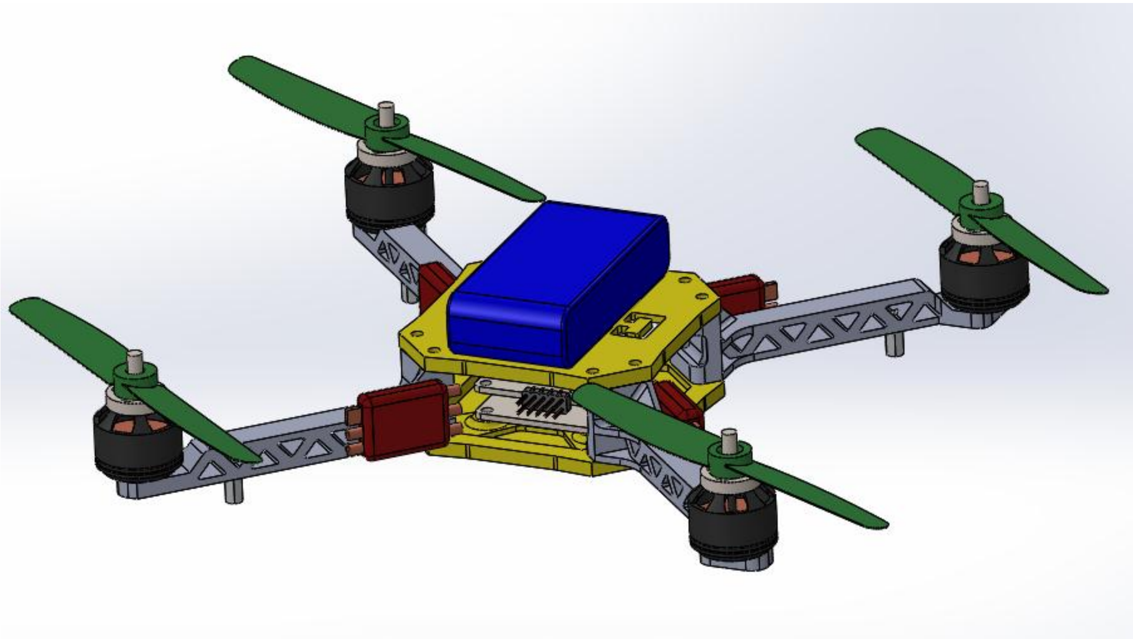
DUMLUPINAR UNIVERSITESI

INDUSTRIAL ENGINEERING

DRONE DESIGN



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WHY?

This type of platforms are very appropriate for teaching, since they integrate a great diversity of knowledge areas such as rigid solid mechanics (moments and inertial tensors, rotational matrices, Euler angles), applied mathematics (quaternions), electronic Power (electronic speed controllers), automation (vehicle control), etc.

INTRODUCTION

Rotating wing aircraft with multi-rotors began to design, and even fly successfully, at the beginning of the last century. They were, however, firstly replaced by the autogyro, whose main rotor is not motorized and subsequently by helicopters given the inherent instability of multiple rotor structures. In the following figures you can see the first known quadricopter and some aircraft with this configuration of the mid-20th century.

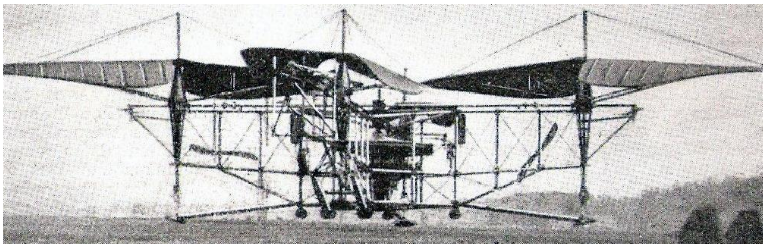

Fig 1

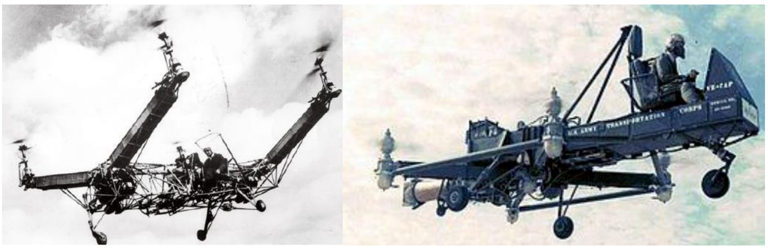

Fig 2

If the stability of the cells (structures of the aircraft) with multiple rotating wings is significantly more complex than the one of the helicopters one could ask what advantages they bring and the reason for their current boom.

In a helicopter the tail rotor is used to compensate for the reaction torque (Newton's third law) produced by the movement of the main rotor. By varying the thrust supplied, the helicopter is also allowed to rotate over the vertical axis passing through the center of the main rotor (yaw movement). In these conditions the power consumed by the tail rotor is not used to obtain vertical, lateral or forward thrust.

However, it is simple to understand that 4 rotors with opposite turns that compensate the pairs of reaction pairs with each other will take full advantage of the power to get vertical thrust. From this point of view the efficiency of the multicopter is superior to that of the conventional helicopter.

The disadvantages caused by the instability of multiple rotating wing structures were solved with the appearance of solid state gyroscopes, accelerometers and magnetometers that allow the integration of angular measurement, acceleration and acceleration functions into very small electronic and electromechanical components And terrestrial magnetic field. Although it is complex to explain the functioning of these devices to know their characteristics in a global way is interesting.

Solid state gyros have several possible configurations. They can use a cylindrical resonator made of piezoelectric elements (their deformation produces accumulation of electric charges) or of micro vibratory structures inserted in a silicone wafer.

The combination of these devices allows to obtain integrated electronic devices capable of measuring angles of inclination, acceleration, and terrestrial magnetic field. Obtaining in this way all the necessary variables to determine the position, speed and course of a moving object. The flight systems for quadricopters of the platform free hardware Arduino, among others, that began its development in Italy in 2005, combine all these functions.
The signals generated by the sensors are processed in a microprocessor which applies several cascading regulation loops, thus achieving that pilot control movements act in combination with the corrections of the flight control system. A piloting known as "fly by wire (fbw)" is developed where the pilot actions do not act directly on the control organs of the aircraft but on the control algorithm that introduces the necessary corrections and compensations.
Fbw systems have their maximum representation in modern fighters, whose aerodynamic design is deliberately unstable to allow evasive maneuvers impossible to perform with conventional piloting. Obviously, the absence of the control system precludes the flight of the aircraft. We can therefore already consider that a quadricopter of any size or configuration is an aircraft of multiple rotating wings, governed by an fbw system that allows the pilot to act On it as it would on a conventional aircraft, adding at the same time multiple possibilities of self-stabilization and correction of flight path and attitude.

AERODYNAMIC PRINCIPLES OF FUNCTIONING OF A CUADRICOPTER

Next, the physical principles that allow the movement of a quadricopter in the 3 spatial axes will be presented in a very simple way. To do this, the axes of rotation of any aircraft will be defined first and then the whole explanation will be developed on a quadricopter with frame in X configuration. The chassis in the form of H and + will be analyzed in other sections but only from the Structural or aerodynamic point of view,

since the physical principles of motion on the chassis in X are understood, the only difference appears for the chassis in + and is easily extrapolated.
Figure 3 shows a conventional aircraft with its three axes of displacement. The movement on the lateral axis that corresponds to bites or ascents is denominated pitch (Pitch). The rotation around the longitudinal axis essential to abandon a rectilinear flight path is called Roll, and finally, the movement around the vertical axis, used in the planes in a coordinated way with the warping is called Yaw.

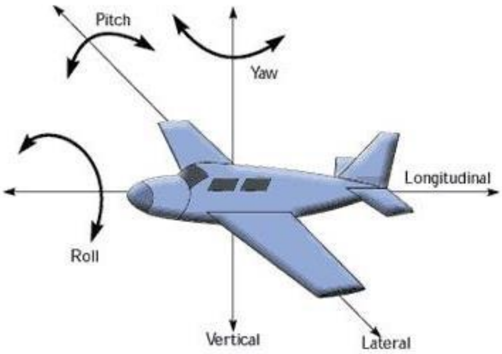

Fig 3

In the case of a multirole aircraft, the names of the movements and the axes are defined identically, although it is necessary to clarify that a forward pitching will be accompanied by the displacement (forward) in the same direction and vice versa (retreat). Equivalently, right and left warping movements will cause the aircraft to move in those directions. Next, all four basic flight situations will be studied: level stationary flight, forward (forward) and backward, right and left (right and left) scrolling and yaw in a clockwise and counterclockwise steady flight.

To understand the operation of a multirotor it is imperative to know clearly the concept of the reaction pair derived from Newton's third law. In a simple way it could be stated, applied to a motor that moves a propeller, in the following way: if a motor to turn a propeller clockwise at a certain speed of rotation n develops a torque of value p, on the bench Of the motor will appear an equal and opposite pair.

As indicated above in the case of a helicopter that pair is compensated in flight by the action of the tail rotor.

A second point to keep in mind is that a torque is the product of a force by the distance to the point where it is applied. From this fact very important conclusions are deduced on the behavior of the system:

1. The higher the torque, the higher the reaction torque.

2. The larger diameter of the propeller, for a same pitch (this concept will be defined later but can be assumed for the moment as the angle of inclination of the blades), greater reaction torque.

Having made these clarifications it suffices to indicate that all the movements of a multirole aircraft will be based on compensating or decompensating the reaction pairs of the different rotors to achieve a resultant in the desired direction. Therefore, the analysis with the simplest situation of level stationary flight will be started.

Level flight

It is assumed that the quadricopter is stationary (hovering) and level. That is, static at a certain height of the floor. In the following graphs the red arrows are perpendicular to the black plane and indicate the vertical thrust (sustencation) of each rotor, the orange arrows indicate the direction of the motor's reaction torque (opposite its direction of rotation) and the green arrow simply points Which would be the nose of the aircraft. The circles in yellow correspond to rotors with sense of clockwise rotation and blue circles to rotors with sense of counterclockwise rotation.

As can be seen from the figure, the quadricopter with configuration in X uses two motors rotating in a clockwise direction and two in a counterclockwise direction. The propellers used have the blades designed antisymmetrically and therefore, although the direction of rotation is opposite all of them produce push down (lift). Understanding the physical principle of the reaction pair is very easy to analyze how the aircraft maintains the flight Stationary: all motors rotate at the same speed, so the reaction pairs are the same on the 4 motors and, since the chassis places them symmetrically, they cancel each other out. There is, therefore, no resulting force that tends to spin the quadricopter around its vertical axis and equal being the thrust of the 4 motors will remain static and level. Obviously, the above analysis is purely theoretical since the multiple aerodynamic effects, residual asymmetries and atmospheric conditions do not allow stable stationary flight if the control and stabilization system does not make small corrections in real time.

Forward and backward pitch (forward and reverse)

Once the stationary flight is understood, the other movements made by the quadricopter will be very easy to analyze. The next situation corresponds to the aircraft passing from stationary flight to a forward pitch that makes the tail rotors up and down the nose rotors.

This effect is achieved simply by increasing the thrust of the 2 tail rotors equally, or decreasing equally the two of the nose. As can be seen from the graph, the red arrows that indicate the vertical thrust are larger in the back than in the previous one.

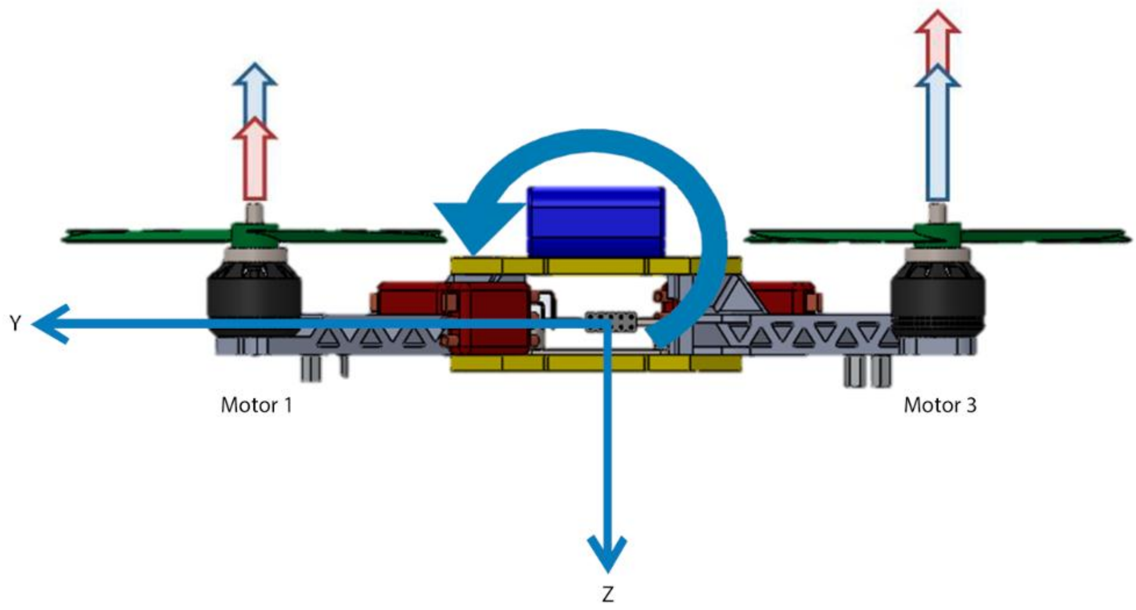

Fig 4

This change in the spin regimes will also modify the reaction pairs. The reaction pairs for this movement are insignificant since the ones corresponding to the rear engines compensate each other equally than the two of the forwards.

It is very important to keep in mind that as soon as the quadricopter moves forward, the force vectors of the motors will not be perpendicular to the ground, decomposing into two forces: one vertical and the other in the direction of pitch. Thus, whenever there is a forward pitching, the aircraft begins to advance in that direction. The control system will ensure that there is no loss of height in this process.

The backward pitching movement opposite to that described above. It should be borne in mind that, as in the case of forward pitching, the backward pitching will be associated with the backward movement of the quadricopter.

According to the Theorem of the Quantity of Motion (TQM from now on) it is necessary that, on the z axis, the forces must compensate the weight, so that the dron is stable and at a certain height. On the y axis, in this state, there are no components of the motor forces.

Equation of equilibrium z-axis:

$$\sum_{i=1}^{4} T_i = mg \tag{1}$$

This does not introduce any variation in the state of the dron if the differential that is added in the motor 3 is the same one that is extracted in the motor 1. In contrast, according to the Kinetic Moment Theorem applied to the mass center one has to Approximation, the mass center is considered to be at the intersection of the three axes previously defined):

$$\overline{GK} = \sum \overline{GP} \times \overline{F_{ext}}(P) \tag{2}$$

$$I_G\dot{\Omega} = \begin{bmatrix}0\\d\\0\end{bmatrix} \times \begin{bmatrix}0\\0\\-T_1\end{bmatrix} + \begin{bmatrix}-d\\0\\0\end{bmatrix} \times \begin{bmatrix}0\\0\\-T_2\end{bmatrix} + \begin{bmatrix}0\\-d\\0\end{bmatrix} \times \begin{bmatrix}0\\0\\-T_3\end{bmatrix} + \begin{bmatrix}d\\0\\0\end{bmatrix} \times \begin{bmatrix}0\\0\\-T_4\end{bmatrix} \tag{3}$$

$$\begin{bmatrix}I_{xx} & 0 & 0\\0 & I_{yy} & 0\\0 & 0 & I_{zz}\end{bmatrix}\begin{bmatrix}\ddot{\theta}\\\ddot{\varphi}\\\ddot{\psi}\end{bmatrix} = \begin{bmatrix}-dT_1\\0\\0\end{bmatrix} + \begin{bmatrix}0\\-dT_2\\0\end{bmatrix} + \begin{bmatrix}dT_3\\0\\0\end{bmatrix} + \begin{bmatrix}0\\dT_4\\0\end{bmatrix} = \begin{bmatrix}d(T_3 - T_4)\\d(T_4 - T_2)\\0\end{bmatrix} \tag{4}$$

As can be seen in equation (4) the moments on the y-axis disappear as T4 is equal to T2. On the other hand, a differential of moments in the x-axis is created, which causes the appearance of an angular acceleration in that axis, giving rise to the movement previously explained. The expression for the angular acceleration that appears is as follows.

$$\ddot{\theta} = \frac{d(T_3 - T_1)}{I_{xx}} \tag{5}$$

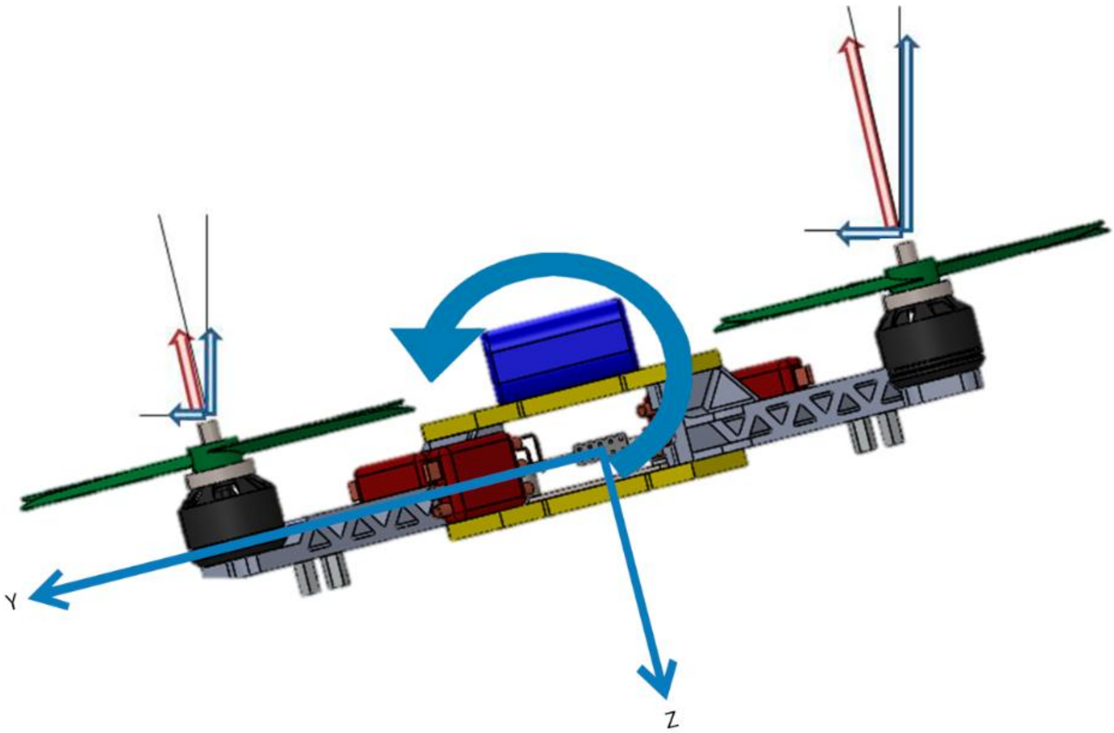

Fig 5

From this simple study we can derive design parameters since it is verified how a longer arm and / or minor inertia we obtain greater accelerations.

Right and left warping (lateral displacement)

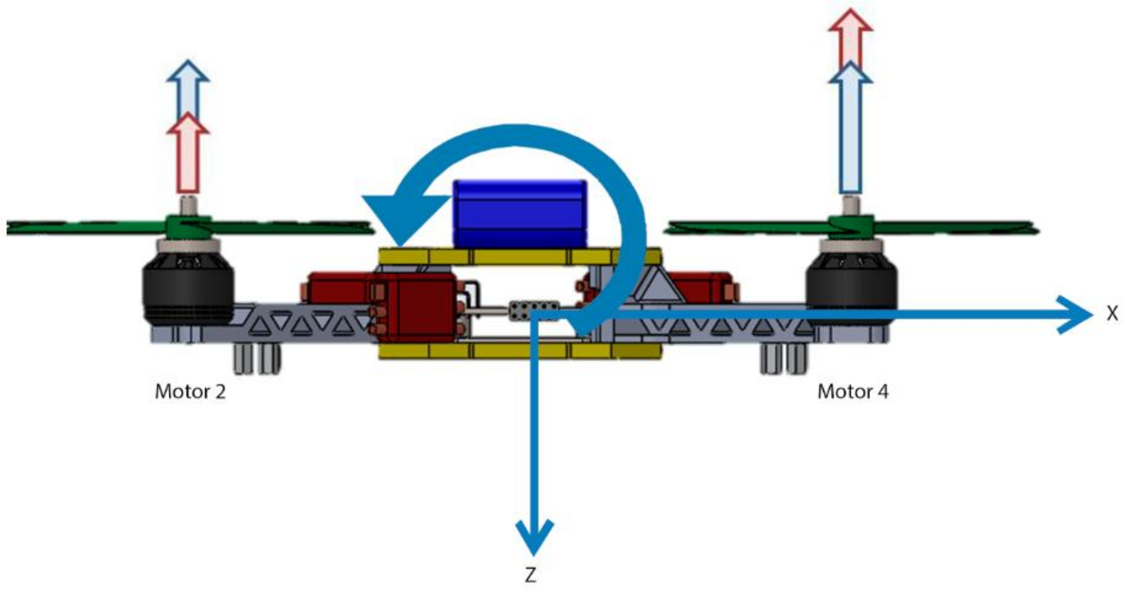

Fig 6

The mechanism for the warping is identical to that described for pitch movements. The only difference in this case is that the pair of motors that increase their speed are the two located on the sides of the quadricopter (seen in its normal direction of advance). Thus, when the right pair of rotors is to be warped, the pair of rotors on the left side will increase their lift, their reaction pairs will compensate each other, and a rotation will occur on the longitudinal axis towards the right side. The warping towards the left side takes place in opposite way.

Just as in the pitching motion the vector resulting from the vertical thrust was decomposed into two forces: one to compensate for the weight of the aircraft and the other forward that produced its advance, in this case the decomposition of forces will give rise to a component Which will cause, in an analogous way, the lateral displacement of the quadricopter.

In this case, the equilibrium equation 1 of the TQM is also fulfilled, and when the TMC is applied, equation number 4 is reached. This time, the forces that cancel out to create momentum are T1 and T3, whereas when a difference Between T2 and T4 a moment is generated on the positive y-axis whose angular acceleration is defined by equation 6:

$$\ddot{\varphi} = \frac{d(T_4 - T_2)}{I_{yy}} \qquad (6)$$

In the same way, a horizontal component appears that generates the translation movement in the direction in which the dron has been inclined.

Stag flight in level stationary flight (turn on itself)

Just as in a helicopter, a tail rotor is necessary to counteract the torque exerted by the blades, the same problem occurs in a multicoptero and, therefore, there are several ways to deal with this problem.

The most common thing in a multicoptero is to have a pair of helices, so the most common thing to control the yaw is to spin half the motors in the opposite direction to the other half, thus the reaction pairs produced by the Helices counteract each other. The disadvantage of this method is the need to have two types of propellers. Because the propellers have a concrete aerodynamic profile, it is not enough simply to put the propellers upside down because, although thrust would be generated, it would not be enough.

Another method is to turn all the motors in the same direction and generate counterparts with some design feature. The main method is to tilt all the rotors from the vertical to counteract the torque produced by the propellers (Figure). In this way, as in the previous case, we can control the variable yaw the speed of two of the four rotors (in the case of the quadricopter).

The alternative, keeping the four propellers rotating in the same direction is to apply a method similar to the one introduced above, where one of the rotors is given a degree of freedom of rotation perpendicular to the arm. This degree of freedom is controlled by a servomotor attached to the flight control and, depending on the rotation of the engine, a yaw is achieved in one direction or another. It should be noted that the rest position of the motor is not parallel with the rest of the motors, but is rotated to avoid an unwanted yaw. This form of control of the yaw is used especially in tri-rotors, where something more of mechanical complexity is necessary to be able to control the yaw.

The last alternative is to place control surfaces at the outlet that redirect the air flow out of the propeller and provide a counterpart. The variation of the angle of these surfaces will achieve the yaw movement.

In our case, the first method will be used since the aim is to simplify both mechanical and aerodynamic design.

The analysis of the movement to be presented below consists of assuming the quadricopter in stationary flight leveled and cause a yaw or twist motion around its vertical axis.

The physical phenomenon on which this movement is based is different from the previous ones. In the cases studied, the reaction pairs of the motors were compensated in pairs so that no force capable of causing their rotation around the vertical axis was induced in the quadricopter. However, for the yaw movement the exact opposite is required: that the resulting pairs of the 4 motors are decompensated and a resultant is obtained in the desired direction of rotation. For this, will also act on the engines in pairs, but this time in pairs located transversely. The following figure (7) shows the distribution of thrust and reaction pairs corresponding to a yaw movement counterclockwise. As shown in the drawing, in order to obtain the reaction torque or resultant rotational force the rotors marked in blue will reduce their rotation speed and with it their lift (vector in red) and their reaction torque (vector in orange) . Simultaneously, the rotors marked in yellow will increase their speed of rotation increasing their lift and with it the reaction pairs.

Obviously, if the quadricopter is not to lose height, the total lift (vertical thrust) must be kept constant. It could be said roughly that the reduction of blue rotor lift is compensated by the increase of that produced by the yellow rotors, keeping the aircraft stable and level. Consequently, counterclockwise rotation occurs as a result of the fact that the reaction pairs of the 4 rotors are not now compensated and a resulting torque / force is obtained which causes rotation about the vertical axis. The yaw clockwise takes place with the same principle but acting on the pairs of motors in reverse.

Regarding the yaw movement of quadricopters, it is important to note that, in general terms, it is less efficient than that of a helicopter. That is, its rotation about the vertical axis tends to be slower. The explanation for this phenomenon is clear: whereas in a helicopter the tail rotor is responsible exclusively for the movement of a quadrant in a quadricopter can not obtain a torque of the same magnitude since the decompensation of the thrust of the engines has Which remain within the limits necessary to keep the aircraft level.

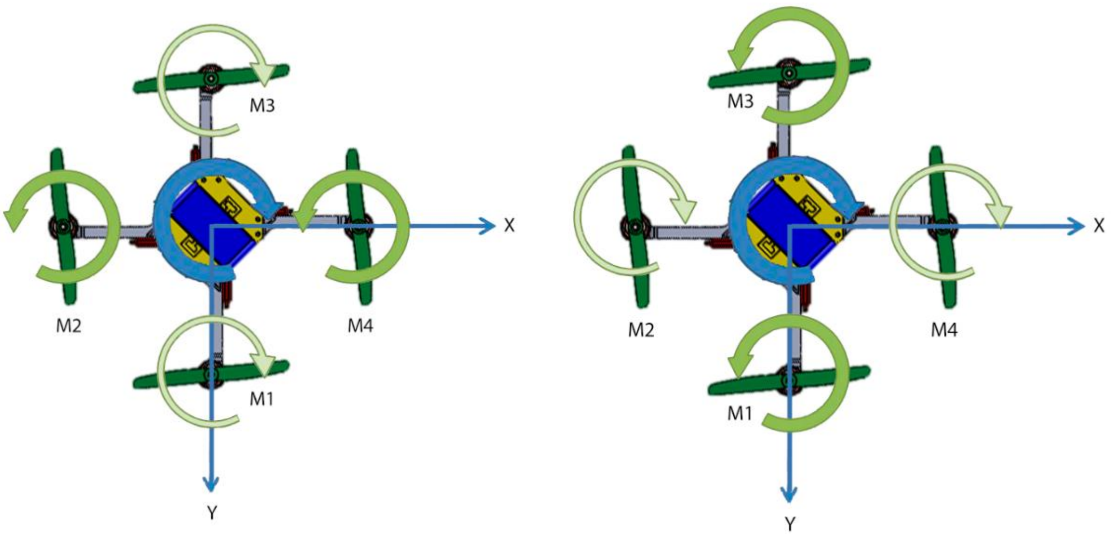

Fig 8

The moment that induces this movement can be expressed according to the following equation:

$$M_{\psi} = \sum_{i=1}^{4} \tau_{mi} = \sum_{i=1}^{4} (I_{zm} \cdot \dot{\omega}_i - \tau_{dragi}) \tag{9}$$

The moment of yaw occurs, as discussed above, by adding up the four rotational moments of the four motors. When rotating two in one direction and the other two in another direction, in steady state they balance and keep the dron stable in the movement of yaw.

On the other hand, by increasing the rotational speed of even motors and decreasing that of odd motors in the same way, that moment is created in the same direction as motors whose speed of rotation is decreased. This happens to preserve the amount of movement. In this case, the dron would be oriented anti-clockwise if the positive z-axis is considered when it points towards the ground or schedule if the images are observed.

There are some special configurations of multirotor equipment where odd numbers of rotors are used to obtain greater agility for this movement. In any case, a high yaw rate is not required for industrial applications, and that type of configuration is usually designed for aerobatics of an acrobatic nature, including variable pitch propellers governed by servos.

The maximum speed of the apparatus will be determined by two factors; The support of

Apparatus, and air resistance. Due to the complexity of the aerodynamic analysis of the apparatus, the aerodynamic resistance of the apparatus will not be determined by analytical form.

We can also determine the maximum slope that can maintain the apparatus maintaining the altitude and therefore its maximum linear acceleration.

$$\theta_{max} = \cos^{-1}\left(\frac{M_{tot} \cdot g}{F_{max}}\right) \tag{10}$$

Where $F_{max} = F_1 + F_2 + F_3 + F_4$

Knowing the angle, we can now determine its maximum linear acceleration.

$$a_{max} = \frac{F_{max} \cdot \sin\theta_{max}}{M_{tot}} \tag{11}$$

TYPES OF CHASSIS OR FRAMES

The frames of the quadricopters are usually classified into three categories: X, H and + and correspond to the structures in the following figure:

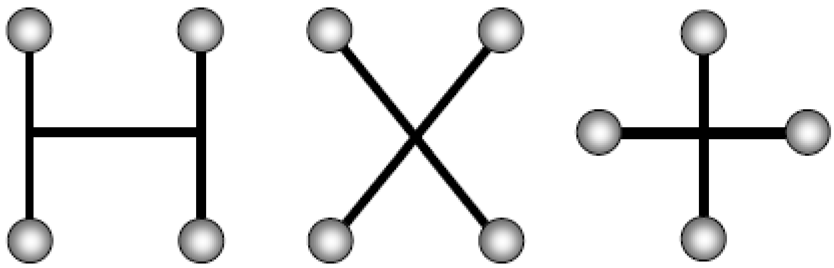

Fig. 6: Configuraciones típicas de los bastidores de cuadricópteros

Fig 9

Regarding the behavior and mode of operation of the quadricopter according to the type of chassis used, it is not necessary to perform a too deep analysis. In terms of operation the configurations H and X are identical. Its only difference lies in the ease and arrangement of space for the location of the elements to be carried by the quadricopter and its structural resistance. In general, the H-structure is more practical if it is intended to locate equipment of a certain size and weight. In fact, it is adopted in a good number of commercial quadricopters.

Commercial frames built in carbon fiber usually adopt configurations in X as the following equipment:

Fig 10

The configuration in + is probably the least used. In this case, the frame coincides structurally with the frame in X. That is, with a frame in X you can choose a configuration in X or in + but the control and the maneuvering procedure is modified.

It is enough to observe figure 9 to realize that the pitching movements will be realized by decompensating the lift produced by the front and rear engines only and that the roll movements will take place when the decompensation takes place on the lateral motors.

Without entering into complex aerodynamic considerations, it suffices to consider only that the forward, backward and lateral displacement movements will occur because of the lift differences only produced by 2 rotors, whereas in an X or H configuration they will occur by the difference of Thrust of the four rotors. It can be said, therefore, without more complex analyzes, that this configuration is less efficient.

PROPELLERS

The analysis of the components of the quadricopter will be started by the propeller since, in fact, it is the most important element since for a multirotor team each propeller is a rotating wing. In this document, the rotary wing is called because with the invention of the autogyro flight theory was developed with rotating wings.

The propeller is responsible for converting the power supplied by the engine into useful power for the flight

A propeller is formed by a set of aerodynamic profiles similar to those presented by the wing of an airplane and with a variable angle from the center of the propeller to the tips. In each section of propeller (each profile) the thrust effect is produced that is no more than the lift.

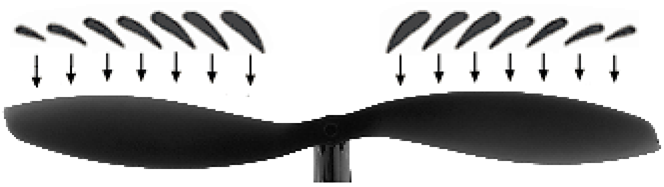

Fig 11 Sections of a propeller

Given the characteristics of this document, it is meaningless to analyze the variables that influence the lift or analyze the fluid dynamics that generate it. It suffices to understand that the movement of the profile of the propeller, in our horizontal case, generates a greater pressure in the back than in the previous one giving rise to the vertical thrust (lift). The following figure (Figure 12) shows the aerodynamic profile of the cross section of a propeller at 75% of its diameter. The highest edge is called the leading edge and the lowest trailing edge. The angle forming the line connecting the leading edge to the air (relative wind) is called the angle of attack.

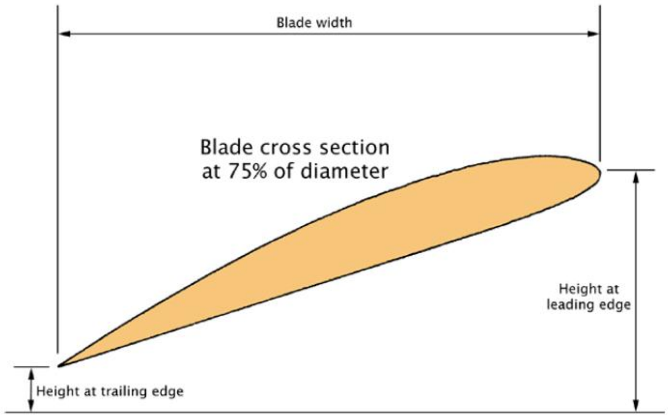

Fig 12 Profile of a propeller

If you look at a propeller like the one in the following figure you can see that the torsion angle of each blade varies from the tips towards the center. It is smaller at the ends and more pronounced at the center. This shape adopted by the blades is due to the fact that the lift produced by an airfoil is proportional to its relative velocity of movement with respect to the air. Therefore, if it is considered that at the ends of the propeller where the radius is greater the linear velocity of the profiles located in that region is higher, it is evident the need to reduce the torsion (angle of attack) of the propeller. This fact in modeling sometimes becomes really extreme. When calculating the linear velocity at the propeller tips of small models where small diameter propellers are used that rotate at speeds in excess of 20,000 rpm, it will be seen that it is at the limit of the speed of sound. When that happens, it passes to the so-called supersonic regime where air can no longer be considered an incompressible fluid. For these cases, the ends of the propellers are designed with negative angles of attack.

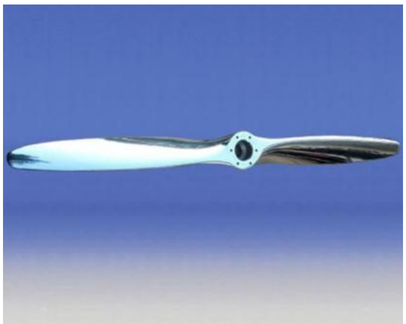

Fig 13

In a quadrotor type helicopter a pair of propellers type puller and other pusher type are required. The names refer to the direction of rotation that the propeller must perform to generate a pushing force in favor of the flight of the vehicle.

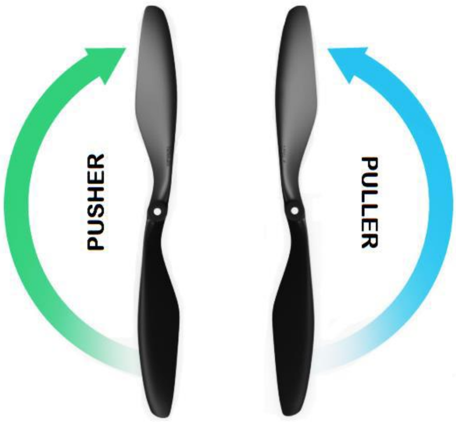

Fig 14

A series of forces acting on any propeller are shown in figure 14 and must be known. The torque that turns it A, the thrust produced by it C (thrust) and the resultant of composing A, B.

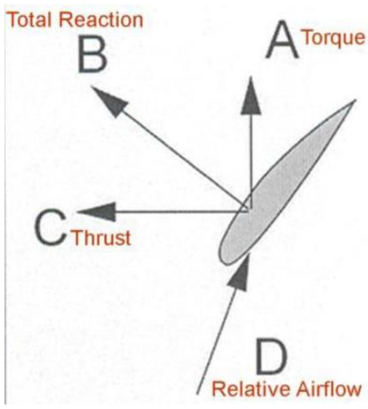

Fig 15

The torque is the one that develops the engine in its turn. It is very important to know that the pair of a moving propeller is a quadratic pair. That is, it is of the form K · V_2 where K is a value that depends on the characteristics of the propeller and V is its speed of rotation.

The fact that the propeller resistor is quadratic has important implications for the operation of a multi-rotor aircraft. Just take the following example into account. It has designed a p-weight quadricopter that is powered by a 2000mAh battery. It is considered that the autonomy is very reduced and the battery pack is replaced by a

4000mAh battery whose weight is 3 times higher. In a first approximation one might expect autonomy to double. However, in order to keep the equipment in flight it will be necessary to lift the extra weight of the battery, for which it will be necessary to increase the speed of rotation of the motors. Since the resistant torque offered by the propeller is quadratic, if we assume, exaggeratedly, that it is necessary to double the speed of rotation, the torque that will develop the motor will be 4 times greater. Under these conditions, Brushless DC engines would consume approximately 4 times more current than in the initial conditions. Therefore, the autonomy would have been reduced to half that available with the light battery.

Although the example is extreme since it is based on the necessity of doubling the speed of rotation, what it pretends is to show that the fact that pairs are quadratic has as serious implications as reasonable increases in the speed of rotation, as a consequence of the increase Of weight, cause consumptions much more pronounced than those would be in case of being a linear pair.

A propeller is defined by two numerical parameters: its diameter in inches and its pitch. For example, 9x5, 10x4.7, 11x3.3 are actual propeller configurations. The diameter does not raise any doubt as to definition. Next, the concept of step will be defined.

The passage of a propeller can be defined as what would advance an aircraft in horizontal flight when a complete revolution occurs. That is, a 9x5 propeller indicates with its 5 "pitch that the airplane flying propelled by it advances 5" forward in each revolution. This step given as the definition of the helix is the geometric step. The actual advance of the aircraft will be inferior due to an aerodynamic phenomenon that in Spanish could be defined as sliding. Without going into complex details of fluid mechanics the slip could be explained intuitively by comparing the propeller with a screw that is screwed into a material. When dealing with the material of a fluid "the screw" does not advance in each turn of the screwdriver the distance that it would in a solid material since it "slips". The following figure shows the previous concept.

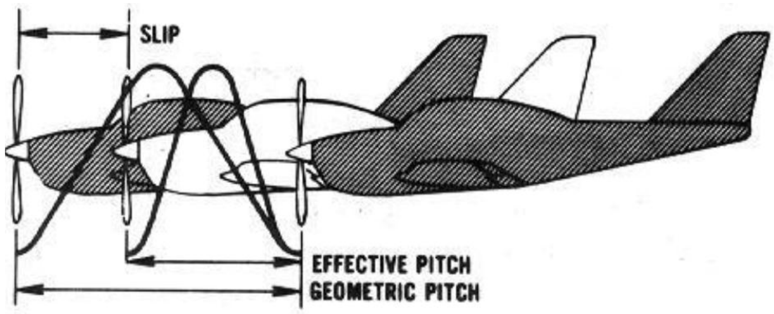

Fig 16

Selecting a propeller

When selecting a propeller for a quadricopter design the first consideration that must be made is relative to its quality of manufacture and rigidity. It is important not to forget that a quadricopter is an aircraft of rotating wings and that, therefore, the 4 propellers are the wings that have to support the weight in static conditions and still more in maneuver where the load factor increases due to the centrifugal force . Therefore, propellers should be selected as rigid as possible, preferably carbon fiber or wood. Any flexible propeller of low cost will deform in the form of cone degrading the flight and the stability of the equipment.

With regard to diameter and pitch, the choice must be made along with that of the motor, although there is a parameter from which can be split: the diameter. As indicated by the performance of a propeller, the greater the diameter, the better the first approximation is (except in the case of serious constraints of space) to try to adapt the diameter of the propeller to that of the frame occupying During the turn as large as possible without obviously interfering between the rotors.

It is necessary to know that the highest aerodynamic performance is obtained by using a 2-blade propeller of the largest possible diameter. This fact has been known since the beginnings of aviation, although that said it might be surprising to see classic airplanes with multi-blade propellers. However, it is sufficient to take into account the space restrictions that a conventional aircraft has for takeoff and landing to understand the need to reduce the diameter by increasing the number of blades. With regard to the design of multi-rotors, the diameter of the propeller should be chosen to encompass the largest possible area of the chassis provided that no tandem aerodynamic interference is achieved, where the vortices of the rotors interact between yes. The following figure shows this phenomenon:

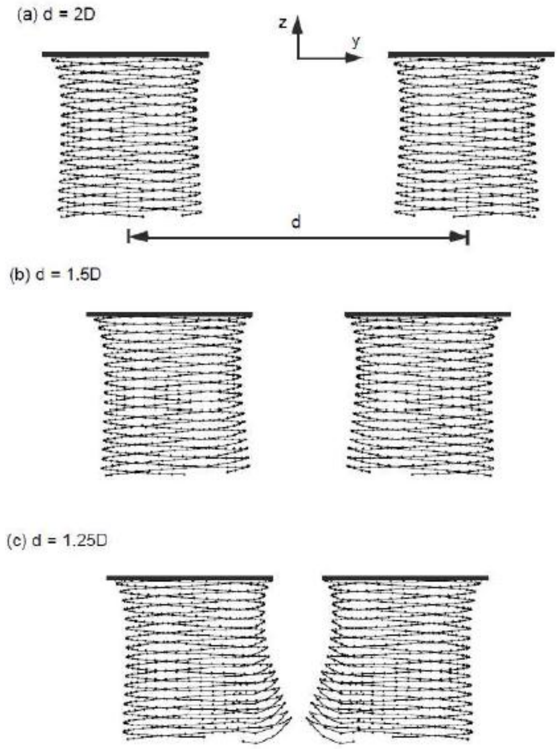

Fig 17

In it the vortices of the rotors have been represented for different distances between axes of the motors. In the figure to the axes of the motors are separated a distance D equal to 2 times the diameter of the propellers. In figure b, 1.5 times the diameter and in figure C to 1,25 times the diameter.

The third figure already shows the effect of tandem vortex interference. Therefore, separations lower than those given by this value should not be used.

Performing a review of the most popular quadricopters: Quantum Nova, Phantom, etc. It is possible to see how the manufacturers have respected both criteria: on the one hand, they have tried to occupy the maximum available area and, on the other, the recommended propellers establish a criteria of distances slightly superior to 1.25.

BRUSHLESS DC MOTORS (BLDC) OR ELECTRONIC SWITCHING ENGINES

Despite the extra complexity in its electronic switching circuit, the BLDCM presents

Several advantages over its counterpart, to name a few: higher torque / weight ratio, less operational noise, longer lifetime, less generation of electromagnetic interference and much more power per volume, practically limited only by its inherent heat generation, whose transfer to the outer environment usually occurs by conduction.

In spite of their performance differentials, the BLDCM's dynamic model can be roughly approximated by the well-known BDCM's. Fig. 17 shows the basic electrical circuit of such motor, where is the voltage applied to its armature, Ra is the armature's resistance, the its inductance, vb = kv! Is the back-electromotive force induced in the armature, kv is the speed constant and! A is the angular speed.

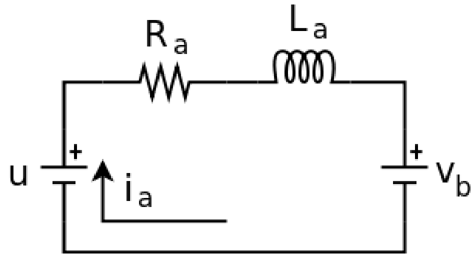

Fig 18

A BLDC can be considered for functional purposes as a conventional DC motor in which the brushes and the manifold have been replaced by electronic equipment which injects the current into the appropriate windings, depending on the position of the rotor, to obtain a torque . However, in terms of electrical engineering, the BLDC is a synchronous machine since its rotation speed coincides with the frequency of the electronic equipment that feeds it. In fact, the control and variation of its speed takes place by controlling the switching frequency of the transistors that are part of the variable speed drive.

To understand this explanation, it is necessary to begin by describing the parts and operating principle of a BLDC.

A BLDC motor consists of two parts, the rotor and the stator. Obviously, the first is the one that moves and the second the one that stays static. Generally, the electric motors have a cylindrical rotor rotating inside a larger hollow cylinder which is acting as a stator. However, in this type of machine are possible 2 topologies: engines "Inrunner and Outrunner". These names that do not have a direct translation into Spanish simply indicate if the rotor is located inside the stator (inrunner) or if the rotor is the outrunner and the stator remains fixed therein.

The following figure shows the structure of a BLDC inrunner, ie the rotor rotates inside the envelope. As can be seen in the graph, the rotor is a cylinder inside which are usually permanent rare earth magnets: SmCo or NdFeBo. The second are the employees currently in modeling applications. The stator is formed by coils wound around polar cores of ferromagnetic material. When current is circulated through the coils, new magnetic poles are created that interact with the permanent magnetic poles of the rotor causing the rotation of the machine. The motor of the graph has 4 poles in the rotor and 6 poles in the stator. As the poles will have opposite signs this configuration is usually designated as 5N5S, ie 5 poles north and 5 poles south. It is not uncommon to find engines with asymmetric configurations where the number of north and south poles is different, especially in outrunner engines that develop greater torque. If you analyze the stator of the machine you can see that the coils of 3 different colors have been colored. This graphic reference indicates, for example, that the green winding of the upper pole is connected in series with the green winding of the lower pole thus forming one of the 3 stator phases. The same happens with the other pairs of coils so that internally they can be connected to a common point: winding in star or forming a triangle whose vertices will be the outlets.

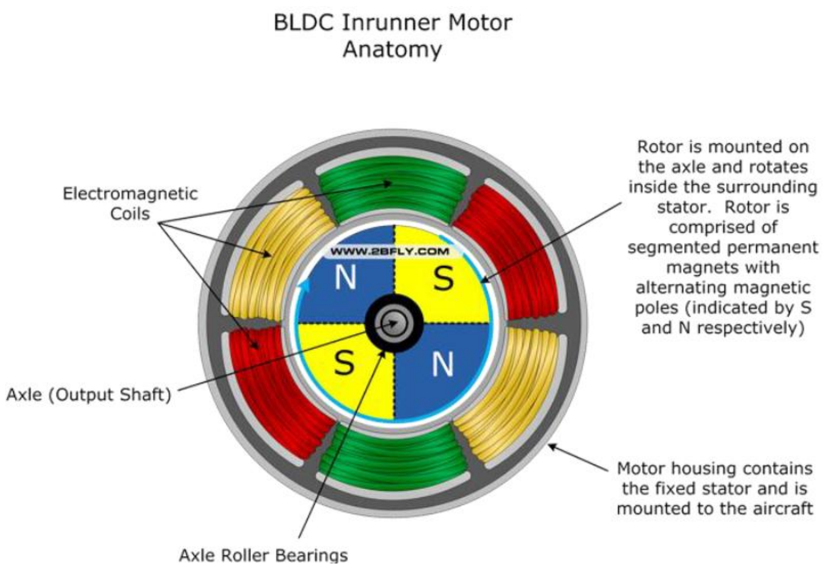

Fig 19 BLDC Motor inrunner

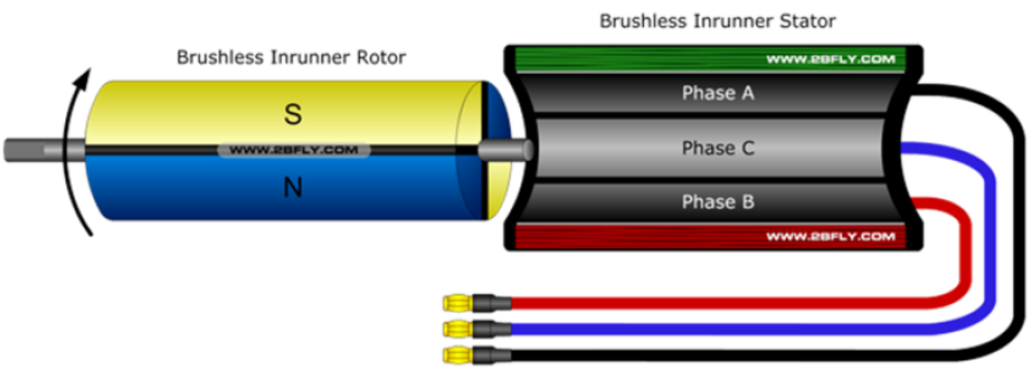

Fig 20 BLDC Motor Inrunner

Figure 19 shows a side view of the inrunner motor, in which it can be seen how the rotor is housed inside the envelope in which are the polar masses on which the windings of the three phases of the machine have been wound.

In the configuration of Figure 19 an outrunner motor is shown. In this case, the poles formed by permanent magnets have adhered to the inner part of the outer shell which is movable and rotates mounted on bearings. Therefore, this envelope with magnets is the rotor of the machine, in the form of drum, that when turning by the outside receives the name of outrunner. The stator winding is mounted on this occasion in the center on the polar masses that are fixed to the back support of anchorage.

Figure 20 shows the external appearance of the motor. In it you can clearly see the anchoring bench located on the right side and how the spin is performed by the outer drum inside which the permanent magnets are installed.

In motors designed with this structure for modeling applications it is very common to find shaft outputs on both sides and mounting accessories that allow them to be anchored to the model in different positions.

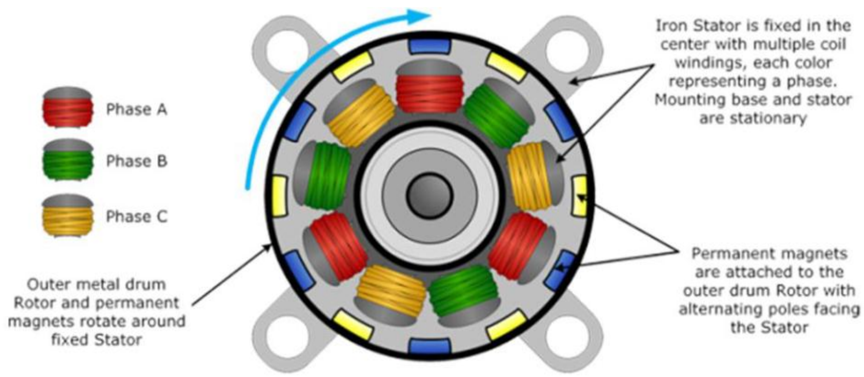

Fig 21 BLDC Motor Outrunner

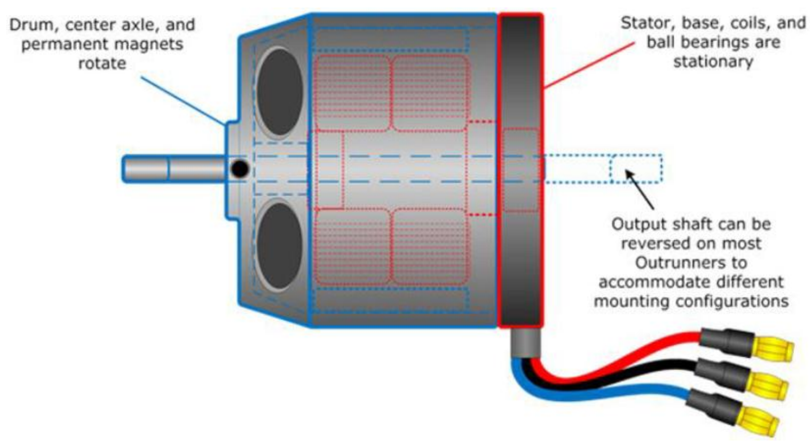

Fig 22 BLDC Motor Outrunner

Although the two types of motor are conceptually identical and equations and operating principle the same, as with industrial synchronous machines their physical topology significantly modifies their characteristics and applications. Without going into more complex details it can be said that the main difference between an external rotor motor and an internal rotor motor is its speed of rotation and its ability to produce torque.

The inner rotor motor is slimmer and longer, so its design allows for much higher turning speeds without significant centrifugal forces. In fact, it is not uncommon to find models where the engine speed exceeds 20,000 rpm. We could say, therefore, that this type of motor is more apt to move small diameter propellers that need to rotate at a high speed of rotation as they happen in the systems called ducted fans for airplanes.

On the other hand, the outer rotor or rotating housing motors are flatter and have a larger diameter. This structure already makes it clear that its speed of rotation will be lower and its torque much higher. In fact, the design of a BLDC disc or rotary drum motor precisely seeks to generate a high torque. One of the most surprising applications of this type of machine, designed in the form of a flat and narrow disc, is its use to perform taxiing tasks (taxiing before arriving at head of track and return to the point of parking) displacing a plane of Line by electric traction. In this way, fuel economy, reduction of emissions and less wear of the turbines are achieved.

In their modeling application they may be considered suitable for moving larger diameter propellers and not very high passages at intermediate speed regimes. In general, it can be said that they are the most suitable type of motor for the design of multicopters.

Principle of operation: electronic switching

So far, the main properties of the BLDC motors have been described but their operational principle has not been indicated. The rotation of the rotor in a BLDC motor is based on what in Electrical Engineering is known as electronic switching. To understand it in a simple way will be used the diagram of figure 18, which will be repeated here for convenience:

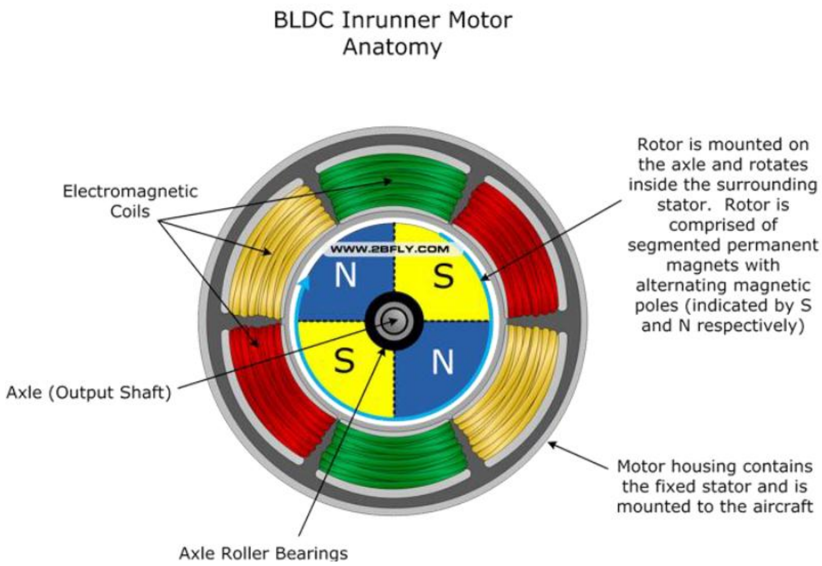

Fig 23

If, in the motor shown in the previous figure, no current is introduced into any of the coils, the rotor remains obviously at rest. Imagine now on the said figure that an external system introduces current in the yellow phase in such a way that two magnetic poles are created, this winding with north polarity. If that happens the north (blue) poles of the rotor will suffer a force of repulsion and the south poles (yellow) one of attraction towards the winding of the same color. It will have been achieved so that the rotor rotates a fraction of a turn.

If the previous situation is maintained the motor would not continue its rotation keeping stable in the previous position. However, as soon as the rotor comes out of the influence of a pair of stator poles the current is nullified in them and introduced into the next the process of attraction and repulsion of the magnets will again take place. Therefore, if the current is injected periodically in the proper angular position, the rotation of the motor will be achieved. These injections and shutdowns of the current are made by electronic switches inside the variable speed drive and is what is called electronic switching. The motor speed is varied by increasing the frequency of activation and deactivation of the circulating currents by the stator winding. This involves changing the frequency of opening and closing the electronic switches of the inverter.

The previous switching process starts from a hypothesis that in practice is not theoretically feasible. It has been assumed that the injection or extinction of the current in each phase is achieved just when the magnetic poles of the rotor are in the correct angular position. In principle, this is not possible unless the motor incorporates a mechanism which informs the variator of the angular position of the rotor. In BLDC motors of industrial applications, for example the car addresses with electric assistance, the motor incorporates on the shaft an encoder (rotary encoder) that supplies the position of the rotor to the variador of speed. The variants existing in the market for these devices are multiple and, since the modeling engines do not use them, it makes no sense to raise more than their existence and the need to inform the variator of the position of the rotor.

If a BLDC modeling engine does not incorporate any external systems that report the position of the rotor how it can function properly? The explanation for this question comes from the use of a control algorithm for the inverter called sensorless control. Explaining a control algorithm of these characteristics is not the subject of this document but a brief indication of its operating principle can be given.

The laws of Lenz and Faraday established at the end of the 19th century that if a magnetic field moves in the surroundings of a set of coils an electromotive force (tension) is induced in them. This law is the basis of the operation of the sensorless control that the variadores of modelismo use to avoid to add systems of measurement of the angular position of the rotor.

The control system operates in a simplified way as follows: The motor starts by injecting the currents for a given direction regardless of the rotor position. This injection of current causes the movement, still uncontrolled, of the motor that can even try to start in the opposite direction to the desired one. During the movement electromotive forces are induced due to the Law of Lenz in the phases that are not injecting current. The measurement of these electromotive forces by the variator allows to estimate the position of the rotor and to ensure that the electronic switching is synchronized with the rotor position. This transitorily unstable situation can be observed if gas is applied very slowly to the motors of a quadricopter in the form of a slight hesitation in the beginning of the rotation of the propellers.

Parameters defining a BLDC motor and characteristic curves

Before indicating the parameters usually obtained from BL = DC motors it is necessary to refer very closely to the two equations that govern their operation. In a BLDC motor it can be affirmed that torque and speed fulfill the following two relations:

$$V = K_1 \cdot N \tag{12}$$

$$T = K_2 \cdot I \tag{13}$$

Where V is the supply voltage, N is the speed of rotation, T is the motor torque and I is the current consumed. K_1 and K_2 are two own constants of each motor that depend on its constructive form, flux density of the magnets, etc.

The constant of the first equation is the one that supplies the most known parameter of the BLDC, usually called kV and indicated in terms of rpm / V (in fact it would be the inverse of the constant indicated in the equation). The constant kV of a BLDC motor, also in a simplified way, indicates the RPMs expected for a given supply voltage. Thus, a 1200 kV motor if fed at 1 V should rotate at 1200 rpm.

The second equation is not related to any data normally supplied by the manufacturer but is very important to understand the operation of the machine. The reading of equation (13) indicates that the current to be consumed is proportional to the constant of proportionality K2 and that the current consumed is directly fixed by the torque that the motor has to develop. This data is very important, as discussed above, because the resistant torque of a helix is quadratic and as indicated in an earlier example if it is intended to double the speed of rotation the torque will be multiplied by 4 and with it the current Consumed.

The other parameters that characterize this type of motor are:

1. The vacuum current (no load current) normally supplied for a certain supply voltage.

2. The resistance of the conductors of the windings.

3. The maximum permissible current (supplied normally along with the maximum time that can develop it).

4. The electrical power absorbed (sometimes in different conditions or for a set of propellers)

5. The number of poles. Normally expressed in the form 15N15S, 14N16S, etc.

For the use of simulation programs, if the motor is not among those selected it is relatively easy to obtain the vacuum current and the resistance of the windings, which together with the number of poles already allows to define the motor completely.

The following graph shows all the characteristic curves of a BLDC motor, and it will comment on the operating point to be chosen for any model.

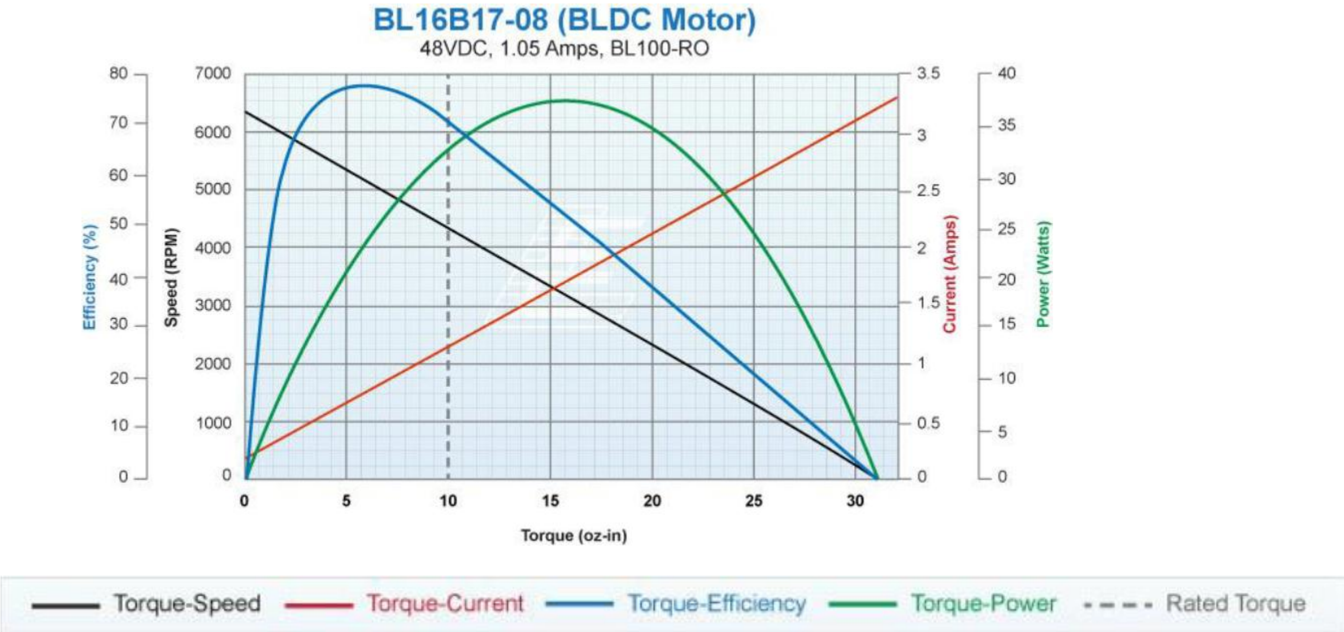

Fig 24

In these graphs you can see all the concepts shown above. If the velocity curve is analyzed in black, it is observed that with the stalled rotor the torque delivered by the motor is slightly more than 30 oz-in and that when rotated in vacuum the speed of rotation is higher than 6000 rpm.

If we analyze the red curve (torque-current) it is clear that equation 13 is satisfied and that the current grows linearly with the pair. The torque zero point corresponds to a current of about 0.2 A. This is the no load current which indicates the motor's consumption to magnetize and overcome the friction losses when it rotates with nothing attached to the shaft.

Finally, the curve of greater interest is the blue one, since in it the performance is represented in function of the pair developed. Performance is an indicator of how much input electrical power is being consumed to produce mechanical power in the shaft. A low yield point indicates that a good part of the electrical power consumed is being used to heat the engine and not to produce mechanical work. Therefore, the operating point at which the propeller is driven to the engine must be as close as possible to the point of maximum performance. Otherwise, it would not only be wasting the battery power but would be overheating the motor.

Normally, the peak performance point of the motor is given with low pairs. For this reason, it is materially impossible to select a propeller which brings the engine to the point of maximum performance. However, selections should be made as close as possible to this value and any combination should be discarded after a simulation yields yields of less than about 70%. The graph shows a line of points corresponding to the selected work point for the motor. It is also possible to observe that a shift to the right produces an increase in the power absorbed and in the circulating current by the motor.

Before finishing with the section dedicated to the engines it is essential to make a comment about its operating temperature. Permanent magnets reduce their flux density as the temperature increases. If the temperature increase suffered by the motor is not very high once the cooling takes place the magnet recovers its magnetism. However, there is a temperature known as the Curie Temperature above which a permanent magnet loses its magnetism.

Therefore, it is necessary to consider 2 aspects of the operation of a permanent magnet motor:

1. Even if the Curie temperature that causes definitive engine damage does not reach, the increase in temperature of the magnets reduces its flux density and causes the motor to degrade its operating characteristics.

2. Once the Curie temperature or values close to it have been reached, the motor will be irreparably damaged.

Therefore, the design should avoid heating the engine as much as possible. An ideal operating temperature would be around 40 ° C and 60 ° C should never be exceeded.

SPEED VARIABLES or ESCs (Electronic Speed Controllers)

Next, the structure of an ESC, its operating principle and some considerations on its choice will be discussed. The following figure shows an excellent diagram of the components of an electronic variator. Analyzing the diagram from right to left the following components can be observed:

1. Output filter capacitor: it is a capacitor used as a filter to eliminate oscillations in the voltage wave that is applied to the motor.

2. Set of 3 vertical branches of legs labeled as FET. These 6 switches are low-resistance channel MOSFET-JFET transistors (the ones they present when they are in saturation, ie, closed). The three phases of the motor connected to the central point of each of the branches. Thus, by performing different combinations with the switches that are

closed and those that are left open it is possible to apply positive, negative or zero voltage to each of the phases of the motor.

3. FET Driver Circuitry: this component is simply an element that adapts the logic outputs of the microcontroller to the voltage and current levels required to enter the gate of the transistors and produce their cutting and saturation (Opening and closing)

4. Microcontroller: in it is the program of governing the transistors. It receives as input the gas signal (trhottle) and also the measurement of the electromotive forces induced in each phase, as it was described when referring to the sensorless control of the BLDCs. Their power comes from the component called BEC present in most inverters.

5. BEC = Battery Elimination Circuit: The BEC is a linear voltage regulator, ie an electronic circuit that reduces the voltage of the batteries and stabilizes it to feed the microcontroller and other components that need a voltage of logical levels, Usually 5 V in our system. The name BEC comes from the fact that in older models it was necessary to have a small additional battery of 4.8V to power the servos, receivers and other electronic circuits.

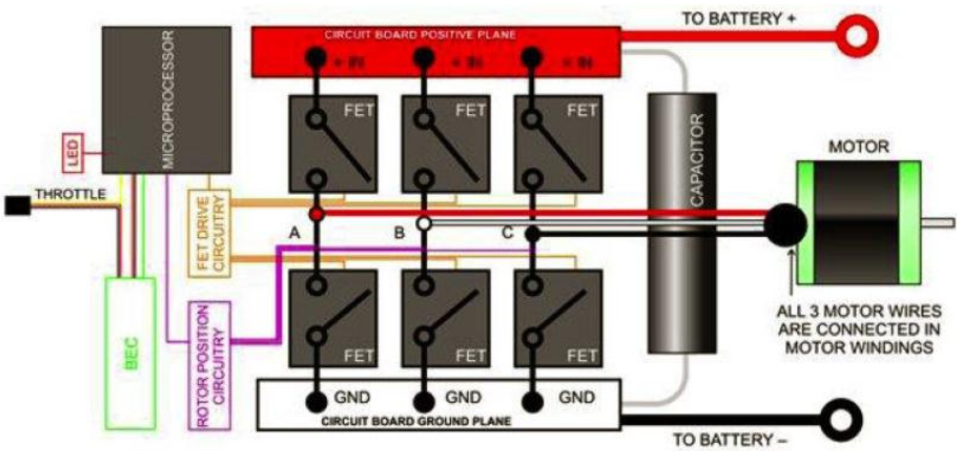

Fig 25

Known its components the operation of the system can be summarized as follows:

1. The inverter is connected to the receiving equipment and an adjustment is made to tell the microcontroller the range of variation of the gas channel input signal. This procedure varies from manufacturer to manufacturer. Some more advanced operating parameters can also be selected, motor braking, motor cut-off when reaching a certain level of battery discharge, etc.

2. Once the calibration process has been done when the transmitter is activated by raising the gas control, the signal enters the microcontroller using its

Sensorless control algorithms vary by raising the opening and closing frequency of the transistors until the desired speed of rotation is reached.

The current market offers an infinite number of variators with very varied characteristics. In the following figure you can see 2 of the most popular.

Fig 26

Fig 27

When selecting it, the following variables must be taken into account:

1. Maximum current you can handle

2. Number of cells for which it is designed (battery voltage)

3. Inclusion or not of BEC

4. Form of programming: from the transmitter by beeps or leds or by passive card.

5. Existence of optocoupling: galvanic separation of the drivers from the transistor doors.

6. Weight.

The electronic speed controller (ESC) is the interface between the control and power stage of brushless electric motors. It receives a signal from a low-power microprocessor and converts it into a three-phase high-power alternating signal.

The signal normally corresponds to a pulse width modulation signal PWM, whose frequency and duty cycle are determined by the factory. The duty cycle is usually in the range of 1 to 2ms and the frequency can take values of 50hz and 490hz.

The following figure shows a PWM signal, where T corresponds to the period and t to the pulse width, both quantities expressed in units of time.

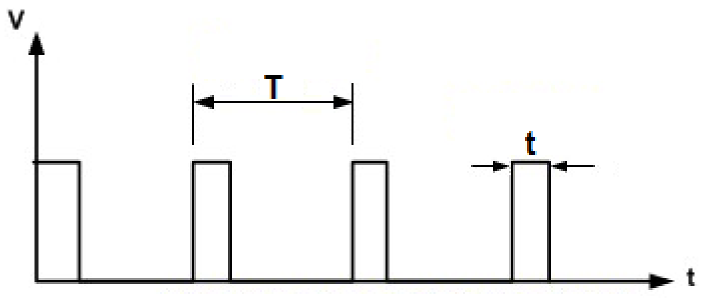

Fig 28

El ciclo de trabajo de una señal PWM se denota y define como:

$$D = \frac{t}{T} \tag{14}$$

BEC AND UBEC POWER SUPPLY SYSTEMS (Battery Elimination Circuits)

The BEC system and its functions have already been commented on in the previous point. Next, the difference between a BEC and a UBEC will be explained. In the first generation of electric models the linear regulator that incorporated the ESC was more than enough to feed all the electronic circuitry of the model. The BECs incorporated into the inverter in the form of linear regulators provided currents of the order of 1 A. The disadvantage of the BEC based on a linear regulator appears when the battery to be used is of a high number of cells. For example, a combination of Lithium-Polymer 4S uses 4 3.7V cells that are freshly charged at 4.2V. Therefore, linear regulator must reduce almost 17V to 5V of the logic power supply of electronic circuits. This reduction in voltage is done at the cost of dissipating the necessary power in the regulator, which is, in the first place, inefficient and secondly causes a high heating especially if it is intended to extract a considerable current from the regulator.

As a solution to this problem appeared the UBECs that are not linear regulators but DC-CC reducing converters. In this case, there is no problem of power dissipation because they are switched sources and the capacity to supply current of the UBEC is much higher and much more in line with the consumptions of the systems that a multi-rotor system incorporates.

The UBECs can be part of the variable speed drive or can be purchased separately as a simple DC converter that reduces the voltage of the batteries and adapts it to power all system circuitry.

Its practical use is extremely simple. Its input is the battery and its output the power connector for all electronic components. In the following figure it is possible to observe a UBEC of 10gr of weight with an output of 5V and 5A.

Fig 29

SELECTING BATTERIES

In the early days of electric modeling, the only available batteries were NiCad, currently banned for domestic use because of the presence of heavy metals. Its weight was high, its energy density low and its capacity of limited discharge. The advantage they presented was enormous strength and durability. Subsequently, NimH batteries with considerably higher capacities were used, but the intensive charging and discharging processes in this type of battery are strongly exothermic and the number of life cycles remained low without having improved the weight problem.

Towards the end of the 90 arrived the first batteries of Lithium Polymer (LiPo) of the mark Kokam arrived in Spain the batteries came in individual cells and the assembly had to be done manually. Its energy capacity was much lower than the current capacity and its discharge capacity about 15 times lower.

From that date until now the development of LiPo batteries and some variants such as LiFePo has been unstoppable. In fact, at this time it is unthinkable to use another compound both for its incredible price drop and for the higher daily benefits. Therefore, a brief review on this type of battery will be made, later the most characteristic parameters that define them will be indicated and finally some advice will be given on the criteria to be applied in their choice.

A Lithium Polymer battery is actually a Lithium Ion Polymer battery. That is, there are no functional differences between Li-ion batteries and LiPo batteries. The differences between the first and the second lie in that the latter the liquid electrolyte is replaced by a solid polymer: polyethylene oxide, poly methyl methacrylate and a number of other compounds. The principle of operation of the battery is based on the circulation of lithium ions between two metal plates that act as anode and cathode.

Although this type of battery is the one with the highest energy density and discharge capacity, it is not without its problems: if they are overloaded they tend to expand to the point of bursting and burning. If they are discharged below a certain threshold, secondary chemical reactions, oxidation of anodes and cathodes occur and the possibility of expansion and fire again appears. In fact, in the early days of its use, many cases of fire caused by failures during the loading process, or the use of batteries that had suffered impacts or deformations, were collected on the Internet.

LiPo battery packs that are used in both modeling and industrial applications are made up of sets of cells connected in series or even in parallel series combinations of series. Each of the cells has a nominal voltage of 3.7V although at full load they reach 4.2V. Their discharge depth (minimum value of the voltage they can reach during use) should not fall below 2,8V.

Next, the parameters that define the commercial LiPo battery packs will be indicated.

Parameters that define a "pack" of Lipo batteries

1. Number of cells: the batteries are designated as nSmP, for example 3S2P. This indicates that the battery in question consists of 2 branches of 3.7V cells connected in series, then connected in parallel. Series-Parallel combinations are used to obtain large capacities, although the most common configurations with all the cells in series are: 1S, 2S, 3S, 4S, etc. The overall voltage of the battery is obtained by multiplying the number of cells by 3.7.

2. Capacity: The capacity of the battery pack is designated by the letter C and indicated in mAh. That is, the data that is given is the amount of energy that the battery is able to deliver. Thus, for example a battery of C = 4000mAh would theoretically be able to provide a current of 4A for one hour reducing its voltage slightly (up to the result of multiplying its number of cells by 2.8V, minimum permissible voltage).

3. Discharge capacity: This data is given in multiples of C, so a battery can be 25C - 50C, 40C - 60C, etc. This indicates what indicates is the maximum current that can be drawn continuously from the battery and that which can be removed for a short time. For example, if the previous packet of C = 4000mAh is labeled as 40C-60C, it means that it is suitable for work by continuously discharging 40 * 40000mA, ie 160 A and briefly 60 * 4000mA or what is 240 A. Obviously, the battery life under these conditions would be divided by at least 40 in the first and by 60 in the second. In actual practice, the reduction is even greater since the behavior is not linear and as the number of discharge C increases its capacity decreases.

All of the above concepts are readily understood in view of a family of curves supplied by a manufacturer of battery packs for modeling:

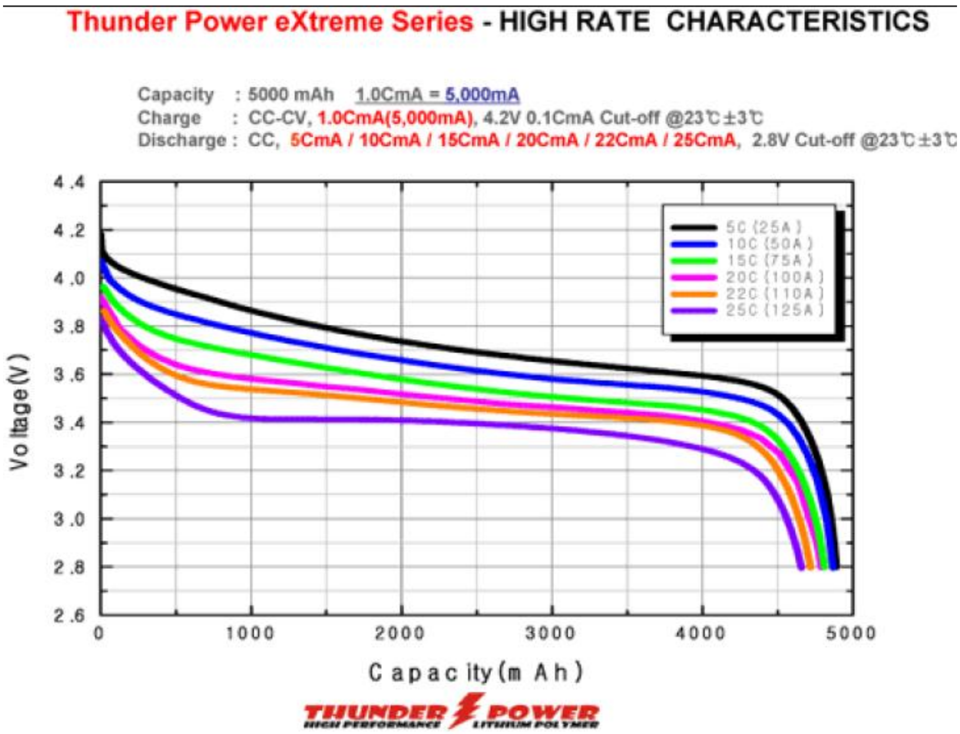

Fig 30

In the family of curves it is possible to observe how as the discharge increases in multiples of C, there is a greater internal voltage drop in the battery and its capacity is reduced.

The correct charging of a battery based on lithium polymers is essential for the durability of the same as to avoid any type of accident or failure that could put at risk the safety of the person who handles it. The voltage of a cell of this type of batteries, as mentioned above, is 3.7 Volts, this voltage is not constant and it varies according to the percentage of charge when the battery is at 100% in 4.2 Volts. So in the process of charging should not exceed this limit as it could damage the battery. Due to this limitation it is necessary to use a suitable charger for LiPo batteries and to select the number of cells that are connected properly, if the value is wrong, there is a risk of overcharging the battery. The vast majority of chargers on the market have built-in a system that auto detects the number of cells connected to avoid risks.

The charger uses a known method of charging constant current / constant voltage (cc / cv), means that during the first phase of charging the battery a fixed current is applied, as the voltage of the battery is close to the limit of 100% , The charger automatically starts to reduce the current level and applies a constant voltage during the remaining stage. The charger interrupts the charge phase once the voltage of 4.2 Volts is reached for each cell.

It is also important to select the current level that the charger will deliver to the battery during charging. It follows a rule in most cases that says that you never have to charge the battery above its capacity, ie above 1C. It means that, for example, if a battery with 2000 mAh capacity is available, a current of more than 2 Amps must never be supplied during the charging phase.

However, as the technology specializes, there are commercially available

Batteries that support 2C, 3C, even up to 5C of charging current. So we can reduce the loading times. If we charge the battery to 1C, it will be completely full in 1 hour, however, if we charge it at 5C the duration of the charge is reduced to 1/5 Hours, 12 minutes.

Also important is the balance of the battery, which allows you to charge all the cells for

Equal reaching the level of 4.2 Volts in each of them without exceeding this limit. Occurs if we have more than one cell, for example, a 3S battery, the charger will reach 12.6 Volts when the charging cycle is completed, however, if the cells have different voltage at the beginning of the operation there is a risk that These differ their level at the end of it. One could exceed 4.2 Volts while the others would not be fully charged. To avoid this and to avoid risks, it is used the balance that loads all the cells alike, with an error of 0.001-0.03 Volts, by reading the voltage of each cell separately thanks to a connection that have all LiPo batteries, the cable Of rolling.

A built-in circuit in the charger allows you to charge the cells using the main power cable of the battery.

Criteria for the correct selection of a battery pack

Exposing all the factors that determine the choice of one or the other battery pack is extremely long and tedious, although a brief indication of the procedure can be given.

1. Choice of number of cells: the most common in these cases is to make the choice of the entire traction system, propeller, motor, variator and battery by means of a simulation program. Or, determine the proper supply voltage that the propeller motor assembly is in the zone of suitable performance and thrust

and from there determine the number of cells. The most common is to use 2S, 3S, 4S configurations.

2. 2. Choice of capacity: capacity must be chosen depending on the desired flight time and the weight of the package. As already indicated above, a reasonable increase in autonomy is not always achieved by increasing the capacity enormously if a large increase in weight is produced.
3. 3. Choice of discharge capacity: the discharge capacity must be sufficient for the maximum current consumed by the battery to be in the range that the manufacturer estimates as suitable for continuous discharge. For example, if my system consumes 100 A, and the capacity of my battery is 5000mAh, its permanent discharge capacity must be at least 20C. In this sense it is very important to note that it is not always a good idea to select batteries with very high discharge capacities. For example, if our capacity requirements in mAh are 2000mAh, and my consumption is 40 A maximum, it is possible to select any battery that has discharge capacity 20C, or a higher value, 25C, 30C, 40C, etc. Although a priori it would seem most logical to choose the battery capacity 40C would be making a mistake. The higher the discharge capacity of the battery the greater its weight and also the greater an internal resistance and therefore its voltage drop. Therefore, by choosing a battery of continuous discharge capacity of 40C we would increase the weight and would have less voltage than selecting a discharge capacity 25C, lighter and with a lower voltage drop. Therefore, this criterion could be summarized by saying that batteries with very high discharge capacities should not be selected if they are not really going to use that property. For this reason in this case the choice of 25C that allows a continuous download of 60 A for an application that will consume a maximum of 40 A is perfectly valid and allows a margin of safety in case any modification of the design increases subsequently the consumption.

GLOBAL TRACTION AND CONTROL SYSTEM: ELECTRICAL DIAGRAM

Finally, the complete connection of a quadricopter with all the elements described will be shown. In them it is observed the connection of all the components to the control system and they do not need more explanation than to clarify that the motors have to turn in opposite directions in pairs.

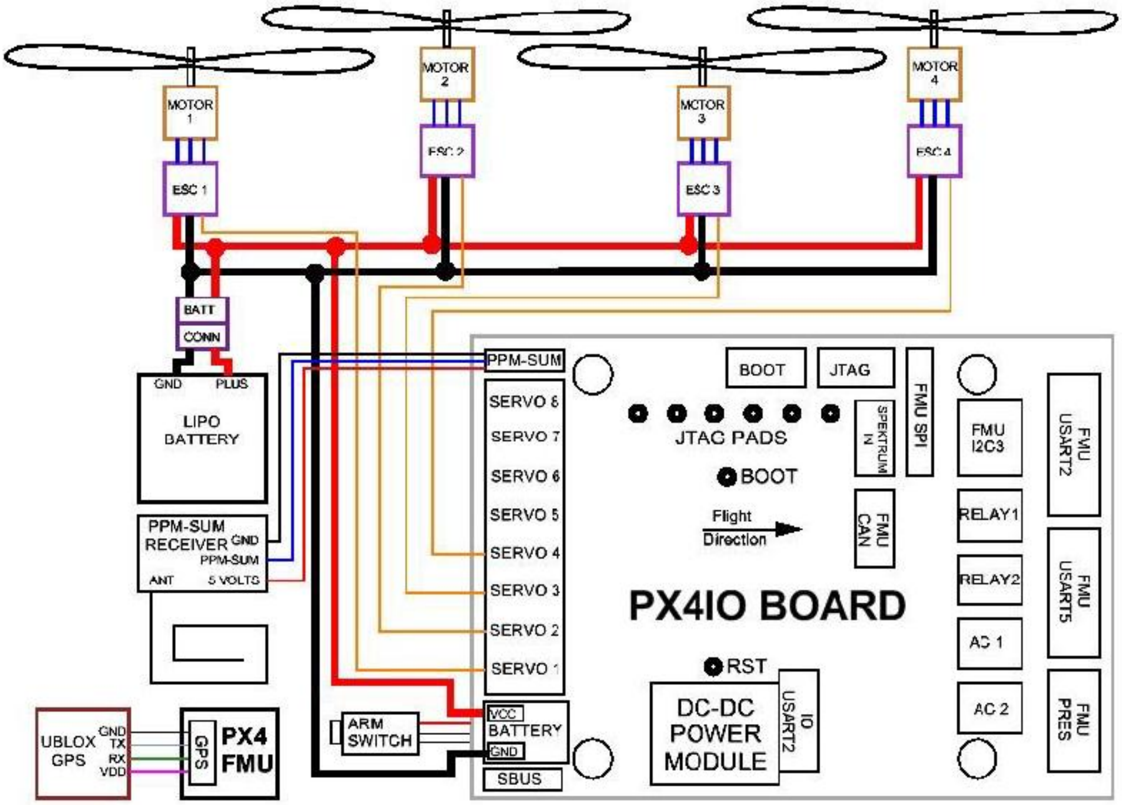
MOTOR 1
MOTOR 2
MOTOR 3
MOTOR 4
ESC 1
ESC 2
ESC 3
ESC 4
BATT
CONN
GND
PLUS
LIPO BATTERY
PPM-SUM RECEIVER
GND
PPM-SUM
ANT
5 VOLTS
UBLOX GPS
GND
TX
RX
VDD
GPS
PX4 FMU
ARM SWITCH
PPM-SUM
SERVO 8
SERVO 7
SERVO 6
SERVO 5
SERVO 4
SERVO 3
SERVO 2
SERVO 1
VCC
BATTERY
GND
SBUS
BOOT
JTAG
JTAC PADS
SPEKTRUM IN
FMU SPI
BOOT
Flight Direction
FMU CAN
PX4IO BOARD
RST
DC-DC POWER MODULE
IO USART2
FMU I2C3
RELAY1
RELAY2
AC 1
AC 2
FMU USART2
FMU USART5
FMU PRES

Fig 31

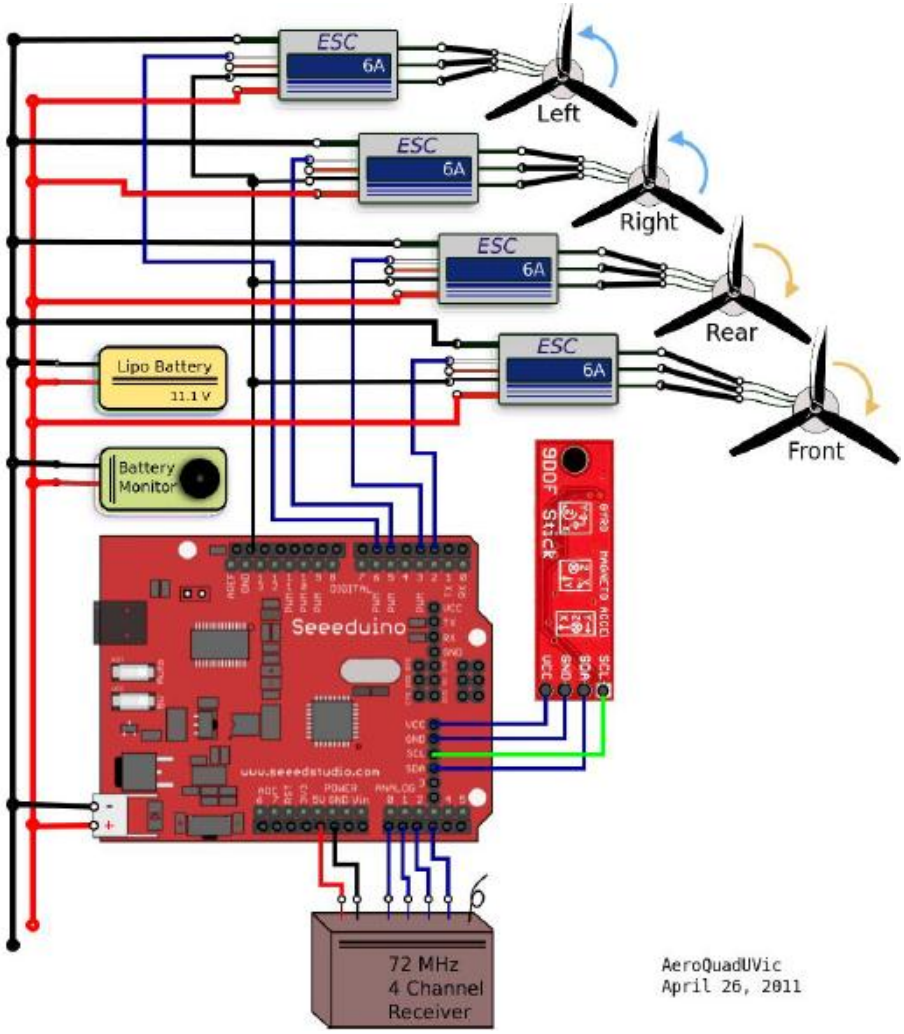

Fig 32

Connections

The batteries usually have two types of connectors already mentioned, the main power cable and the roll wire. The first is responsible for delivering and receiving energy

Which has the battery, the second is responsible for performing a correct balance of the battery cells as explained above.

Fig 33

Fig 34

Fig 35

Fig 36

For each of these cables there are many connectors, whose choice will depend on the use of the battery and the power requirements of the selected design, all of them have safety mechanisms that avoid inverting the polarity when connecting them.

The power cable connectors are as follows:

JST Connector: A small connector used for requirements up to 5 amps nominal. Used in batteries of reduced capacity, below 1500 mAh, to power the motors of very small UAVs and the onboard electronics of the models of a higher range.

Dean Ultra connector: A widely used type of connector whose price is relatively high compared to its competitors, can withstand a rated current level of up to 50 Amperes.

EC3 connector: Bullet type connectors capable of withstand a continuous current of 60 Amps. The "bullet" type, seen in the picture, is very popular in high power applications thanks to the fact that they have a larger contact surface.

EC5 Connector: Larger version of the EC3, with 5 millimeter pins, increases the contact surface thereby increasing its rated current capacity as it can reach up to 120 amperes.

Connector XT-60: One of the most popular connectors in the market for model aircraft thanks to its good value for money. Just as the EC3 connectors use "bullet" technology when making the connection and are capable of supporting currents of 65 Amperes. The protective case is made of nylon that does not melt when welding, and its shape makes them easy to connect and disconnect. There is a higher version able to withstand an intensity of up to 90 Amps at rated speed. In turn the connectors of the cables to perform the rolling are also of many types and will depend on the manufacturer brand, being the type JST-XH the most used. There are other models such as Thunder Power, Polyquest and JST-EH.

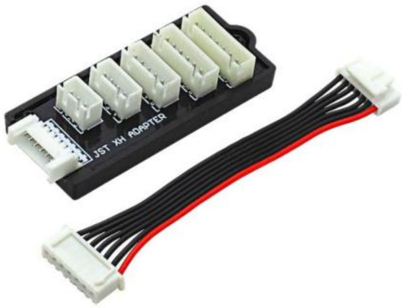

Figura 37

When designing the feeding and loading system, it is necessary to take into account the uniformity of the connections made before proceeding to purchase and choose the most suitable option, most specialized manufacturers offer versatility when it comes to the manufacture of the battery to incorporate the connector that best meets the needs of the project.

Power Distribution Board

Another of the main elements of unmanned aerial vehicles of the multi-rotor type is the power distribution plate, which is responsible for distributing the power of the power system between the different motors. This board is a printed circuit capable of withstanding high levels of current that has a series of ports in which the different elements are connected, there will be a port in which the terminals of the battery (or alternative power system) will go through Of the internal circuit of the plate will be connected to the power outputs of the same whose number will depend on the amount of rotors that own the aircraft. The most conventional only have this distribution circuit power, in the market can find others that also include a circuit that provides power or transmission of signals of a voltage lower than the electronics of the aircraft, as long as a system Additional power supply.

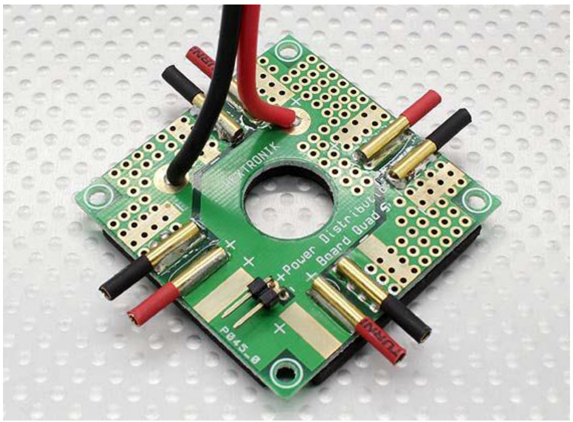

Figura 38

The plate, as its name indicates, is responsible for distributing the power but does not have any element to know how to do it, it is the drive associated with each motor that is responsible for requiring adequate supply of the battery in each Moment in line with the orders received from the flight controller. If a motor has to rotate faster, to perform whatever the movement, the inverter connected to the distribution board will be in charge of letting the necessary power to the winding of the motors so that it turns at the desired speed.

When choosing the right plate, you have to take into account the maximum current flow you can have, this occurs when all motors rotate at maximum revolutions.

The distribution plate must be able to withstand the nominal current flow rate when all motors require maximum supply, leaving a safety margin to avoid possible breakdowns, this value is given in Amperes and must be provided by the manufacturer. The distributor plate is generally placed in the body of the aircraft as centered as possible for a better reach with all the variators and associated motors, because the amount of energy that circulates through it is an element prone to heat so it should Be provided with the maximum possible ventilation.

Flight Controller

The flight controller is the brains of the aircraft, capable of rotating the engines in the right way to achieve the desired movement by the ground controller or following the program guidelines in automatic flight.

It is a circuit of variable complexity that has a series of inputs and outputs, as well as a series of built-in sensors that determine in real time the position of the aircraft. The controller is in charge of processing both the information received by the sensors and the address data to send, through a series of algorithms, the appropriate commands to the motors using PWM signal for the correct flight.

The number and quality of sensors incorporated by the controller varies by model.

Some carry a simple gyroscope that indicates the orientation in the space of the aircraft, however, most of the drivers currently used incorporate an Inertial Measurement Unit (IMU). The IMU is an electronic device capable of measuring and reporting both the speed of the aircraft, its orientation and the gravitational forces acting on it. To obtain this data is provided with accelerometers, gyroscopes and magnetometers

The controller can also receive another series of status data through other types of sensors such as a sonar or laser that indicates the distance of the vehicle to a point. Another device that usually includes the flight controllers of this class of vehicles is a GPS unit, capable of giving real-time information of the geographical coordinates of the aircraft. In addition to tracking the position of the UAV, the inclusion of GPS allows to perform waypoint flights, three-dimensional reference coordinates, which allows the aircraft to follow a route established by the user automatically between a number of locations.

Thanks to the information obtained by the controller, it is able to perform many tasks, depending on the ability of each will be able to develop more complex or less flight capabilities.

Depending on the task to be performed the aircraft will choose one type of controller or another, as we increase the degree of complexity and the capabilities of the same, will also increase its price.

It is also important to take into account when choosing the flight control system the ability to modify the programming thereof. Most systems

Available are closed systems that provide the services described by the manufacturer, however, if the user wants to modify the behavior or include new features, there are open source devices on the market. A microcontroller board can also be programmed to carry out the tasks performed by the controller.

Inertial measurement unit

The inertial measurement unit, known as the IMU (Inertial measurement unit), is an electronic sensor that measures the velocity, orientation and gravitational forces of a mobile system. This sensor owes its development to the evolution in MEMS microelectromechanical systems, which in the 1990s saw the emergence of the first commercial products; Among them are the inertial sensors that were developed by the company Analog Devices Inc. for automotive applications. (MEMS Microelectromechanical Systems)

Fig 39

A system for determining the attitude of a mobile device is composed of gyroscopes, accelerometers and magnetometers which together represent an inertial unit of nine degrees of freedom (9DOF). The gyroscopes alone can not provide a perfect measure of the rotational movements of a UAV, as they are commonly affected by external noise and tend to drift continuously. Therefore, it is necessary to incorporate magnetometers and accelerometers (the latter are very sensitive to vibrations but in the company of a gyroscope it is possible to differentiate between vibration and rotation) by means of a sensorial fusion algorithm. (Fux, 2008)

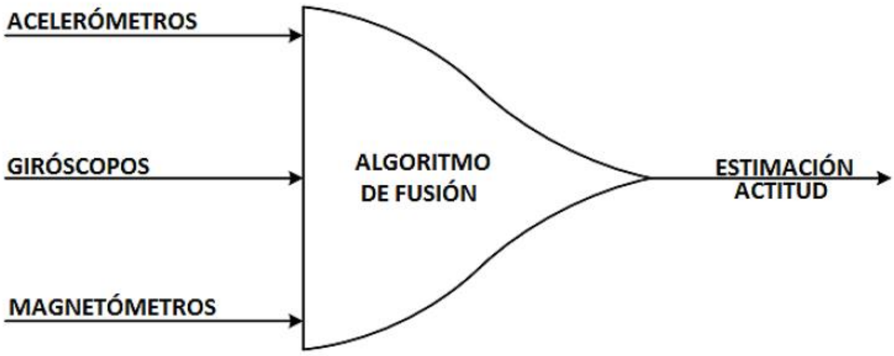

Fig 40

Accelerometer

An accelerometer is a sensor that measures your own acceleration or specific force. This can be thought of as a suspended mass which is attached to two springs on its sides, as shown in Figure 40a.

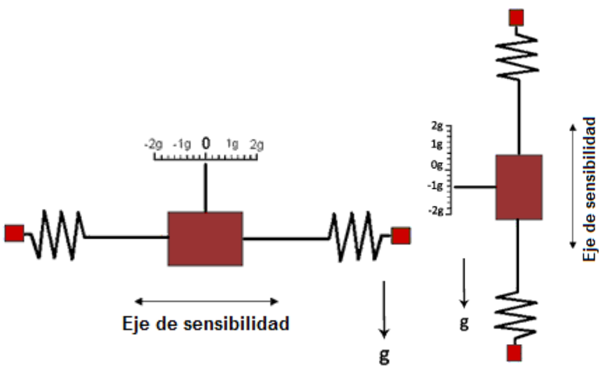

Figure 41 a) Test mass in horizontal position. B) Test mass in vertical position. (VectorNav Technologies)

This mass is known as the test mass, and the direction in which it can be displaced is known as the axis of sensitivity.

Due to the gravitational force, it is necessary to analyze the spring mass system vertically, so that gravity acts parallel to the axis of mass sensitivity, as shown in Figure 40-b. It will be assumed that the accelerometer will measure both the linear acceleration due to motion, and the pseudo-acceleration caused by gravity. It receives this name because the acceleration of gravity does not necessarily result in a change of speed. This offset caused by gravity must be removed from the accelerometer measurement. (VectorNav Technologies)

Gyroscope

Typically used is the vibrating structure MEMS gyroscope, which detects the variation of the speed of rotation on an axis. It is called a vibrating structure because when rotating the gyroscope on an axis, by Coriolis effect, a vibration is produced that is measured by capacitive plates. The signal generated by the plates is treated to be proportional to the angular velocity.

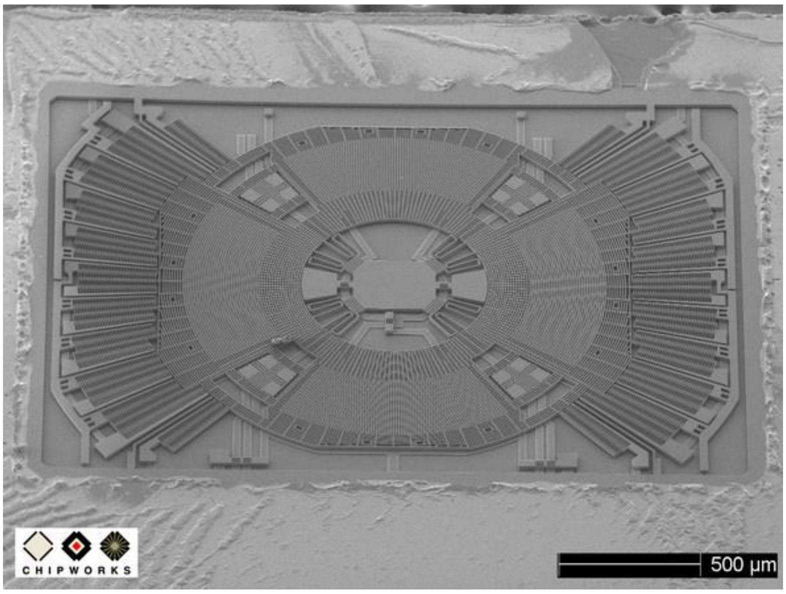

Fig 42

MEMS-type gyroscopes are commonly affected by various sources of error; The most common one appears when the gyro presents a measurement different from zero even though it is immobile. This error influences during the calculation of the angles of inclination, through methods of numerical integration. This factor can be corrected by determining the offset present in the measurement over an extended period of time in still state. (VectorNav Technologies)

Magnetometer

This sensor is based on the Hall effect, although it is not the only one. The Hall effect on these sensors can be described as the situation in which a current carrying semiconductor is placed in a magnetic field, the semiconductor load carriers will experience a force perpendicular to the magnetic field and current. At equilibrium a voltage will be created between the corners of the semiconductor.

The processing of this voltage will allow to know the value of the applied magnetic field. The measurement delivered by the sensor is the result of the addition of the earth's magnetic field to the fields generated by the objects near the sensor (VectorNav Technologies). The latter is considered as a disturbance, which is divided into two categories; The first is known as hard iron, which are all objects that have a permanent magnet, such as motors. The second category is called soft iron which are all those ferromagnetic objects that deflect the magnetic field perceived by the sensor. (Bouabdallah S., Design and control of framers with application to autonomous flying, 2007). The placement of several sensors of this type in a strategic way, also allows knowing the direction of the field lines.

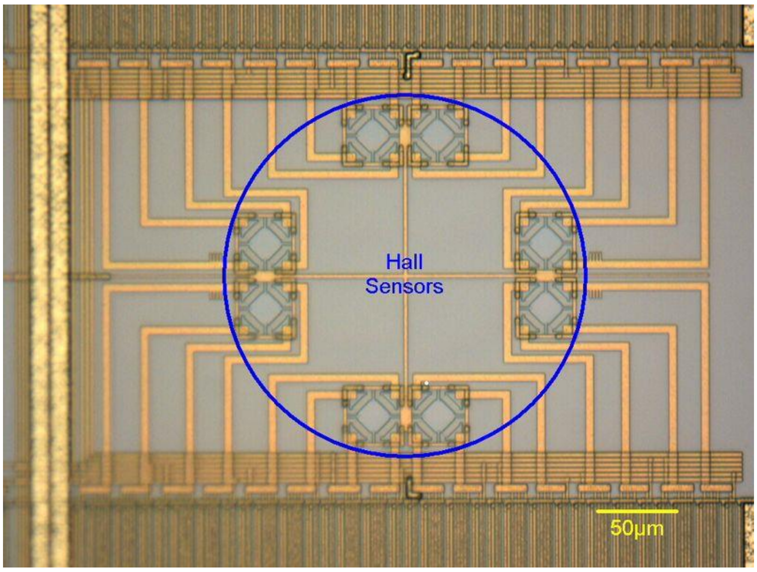

Fig 43

Wireless Communication Modules

In the field of microcontrollable mobile devices, the two most widely used technologies are communication via infrared signals and communication via radiofrequency signals. (Ferrer Ferrer, 2012)

O Infrared communications systems offer significant advantages over radiofrequency systems. When using light as a medium, these systems have a channel whose bandwidth is very large and is not regulated anywhere in the world. Infrared systems are immune to interference and radio noise, but suffer from degradations caused by infrared noise in indoor and outdoor environments, mainly from the sun and fluorescent and incandescent light sources. (Zamorano Flores & Serrano Moya, 2002)

An example of infrared systems for outdoor environments is the Earth link AstroTerra Corporation, which in optimal weather conditions can reach distances of 3.5km and transmission speeds of 622Mbps. The main application of this product is the interconnection of high-speed networks, such as fast Ethernet, FDDI and ATM. For indoor environments, an example is the use of IrDA standard transceivers whose price is less than $ 5. (Zamorano Flores & Serrano Moya, 2002)

O Unlike infrared communication, in radiofrequency systems, the use of the frequency spectrum is regulated by the International Telecommunication Union (ITU), which defines the spectrum range where it is necessary to acquire a license to operate. Within the radiofrequency communications we can find a wide range of protocols: ZigBee (IEEE 802.15.4), Wireless HART, Bluetooth, WiFi, WiMax, among others. (Ferrer Ferrer, 2012).

Electrical Parameters

The electrical diagram of the device is as follows:

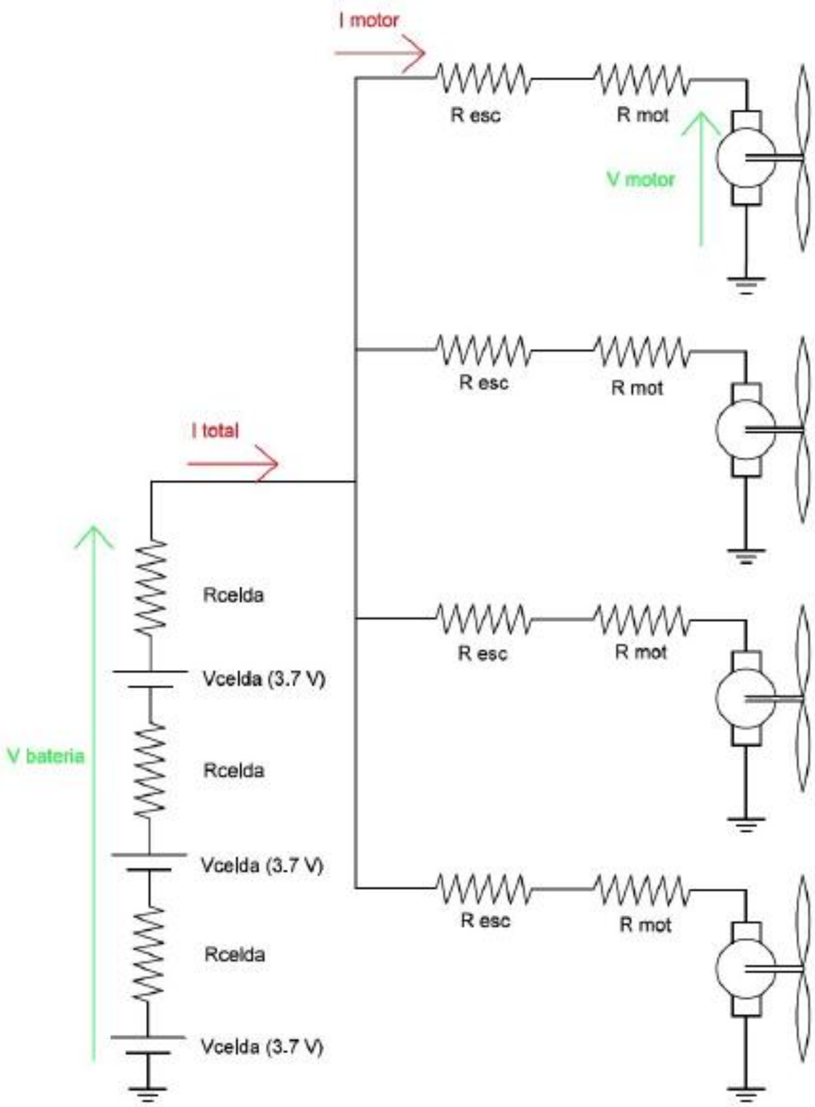

Fig 44

Currently BLDC (Direct Brushless Direct Current) motors are classified mainly according to the parameter Kv, where:

$$K_v = \frac{RPM}{Voltios} \tag{15}$$

We know that:

$$K_t = \frac{30}{K_v \cdot \pi} \tag{16}$$

In this way we obtain the parameter:

$$K_t = \frac{Par}{Amperios} \tag{17}$$

Knowing the angular velocities and the necessary force we can now relate them to the voltage and current of each motor:

$$\frac{RPM}{K_v} = V_e \tag{18}$$

$$\frac{J}{K_t} = I_e \tag{19}$$

Where Ve is the input tnesion and Ie is the current. However, we must consider the resistance of the connectors and cables to the input as well as the resistance of the connectors, so that the equations remain as follows, where Rc is the resistance of connectors and cables:

$$\frac{RPM}{K_v} = (V_e - R_c \cdot I) \tag{20}$$

The term Rc also includes the internal resistance of the battery. In general, lithium batteries, see their maximum discharge capacity determined due to internal resistance. However, it is not typically provided by manufacturers. There is no standard by which to classify the quality of aeromodelling batteries and the differences between batteries of different prices are not clear.

We must take into account the current that consumes the motor without load, which represents the current of Vacuum Io, so the above equation is:

$$J = K_t I_e - K_t I_0 \tag{21}$$

Then:

$$\frac{J + K_t I_0}{K_t} = I_e \tag{22}$$

We can calculate the input electrical power as:

$$P_{e,entrada} = I_e \cdot V_e \tag{23}$$

AntiSpark System

Next, the design of a system in charge of avoiding the undesirable ones is detailed

Sparks when connecting the battery system. Due to the high level of voltage and charge of the

Batteries, when these are connected to give power to the engines a spark occurs that can end up damaging the connectors and be dangerous for the user of the aircraft. The spark occurs because the battery voltage exceeds the breakdown voltage of the air gap between the two connectors. The way to avoid this unwanted phenomenon is to perform a preload of the input capacitors of the electronic circuit to be fed, the inverters in the case studied. This will increase the breakdown voltage and eliminate the problem.

Therefore, a system must be designed to allow the capacitors to be precharged

Of the inverters, before making the total power connection. The solution is decided to circulate a small current through a resistor for a short time to charge the capacitors and then divert the current flow through another circuit that offers less impedance to power the circuit.

This is achieved by including a more capacitive transistor system. In

The following figure shows the proposed circuit.

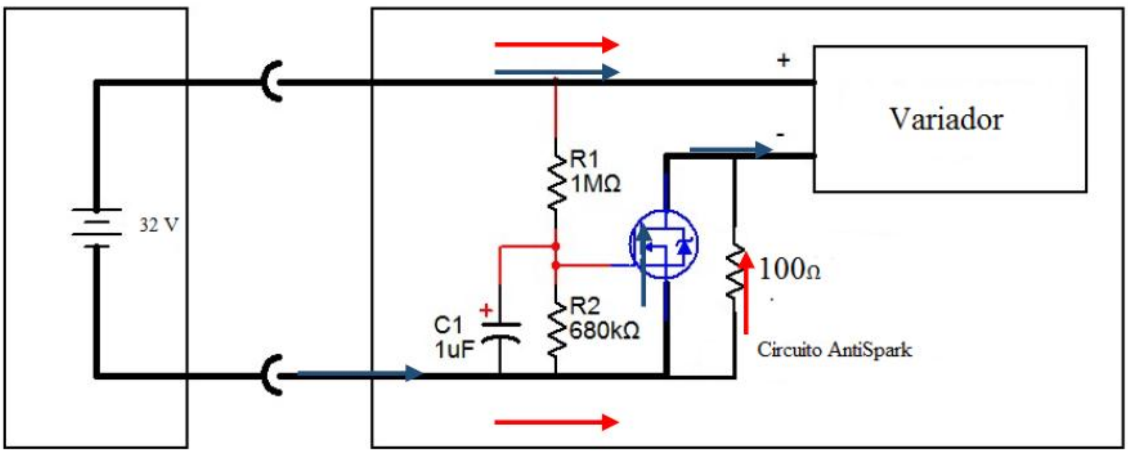

Fig 45

At first the transistor is open so the current flows as indicated by the red arrows, through the resistance of 100 Ω that will provide a limited current to charge the capacitors of the inverter. The transistor closes after the charge time of the capacitor of the circuit

Will depend both on the capacity of the unit and on the resistances involved in the

Scheme, according to the following formula:

$$V(t) = V_f\left(1 - e^{\frac{-t}{RC}}\right) \tag{24}$$

Being:

V (t): The voltage in the capacitor

V_f: The voltage between the capacitor plates

T: The charge time of the capacitor

A: Circuit resistance in Ohmnios

C: Condenser Capacitance

The chosen values of the circuit components are obtained in such a way that

The charge time of the capacitor thereof, is sufficient for the capacitors

Of the inverters are charged through the resistor. To know this time value

Just solve the equations of the capacitor.

The voltage between the capacitor plates is obtained by solving the mesh so that:

$$I_f = \frac{V_{bat}}{R_1 - R_2} = \frac{32\ V}{680\ K\Omega + 1M\Omega} = 1.9048 \cdot 10^{-5}$$

$$V_f = I_f \cdot R_2 = 1.9048 \cdot 10^{-5} \cdot 1M\Omega = 19.05\ V$$

The value of V (t) is given by the circuit voltage at that point, ie, the voltage

Necessary to the input of the transistor to close the circuit. In the case of the transistor used, which will be detailed later, this value corresponds to 3 Volts.

So that:

$$t = -(R_1 + R_2) \cdot C \cdot \ln\left(1 - \frac{V(t)}{V_f}\right) = -1.68M\Omega \cdot 1\mu F \cdot ln\left(1 - \frac{3\ V}{19.04\ V}\right) = 0.28s$$

Time value more than enough to cause the load of the drives before the main power circuit closes. Once the transistor operates as a closed circuit the current will flow where the blue arrows in the diagram of Figure 44 indicate. In this case it is observed that the energy will circulate through the transistor whose impedance must be the smallest possible to avoid losses by dissipation and Maximize the efficiency of the batteries.

Other parameters:

Engine Efficiency:

$$\eta_{mot} = \frac{P_{mec}}{P_{ele}} \tag{25}$$

Battery duration:

$$Duración = \frac{I_e}{\frac{Capacidad}{10000}} \tag{26}$$

Calculation of parameters at maximum power

In this case, when simplifying BLDCs as traditional DC motors, we will assume that the maximum is given by applying the full voltage of the batteries to motor terminals. In this case we will need to solve the following system of equations where cp represents an empirical constant that is determined by the density of the air and by the aerodynamic profile of the propeller

$$\begin{cases} RPM = K_v \cdot V_{mot} & (27) \\ P_e = C_p \cdot Pitch \cdot D^4 \cdot RPM^3 & (28) \\ I = I_0 + \dfrac{J}{K_t} & (29) \\ V_{mot} = V_{bat} - I \cdot R_{tot} & (30) \end{cases}$$

Calculation of parameters at maximum efficiency

The intensity of an engine at the point of maximum efficiency is determined by finding the maximum of equation 25 replacing the mechanical powers by the product of equation 21 and 20 and the electric by equation 23. For this we assume conditions of flight of 80 % Of engine speed, represented by parameter FP. In this way, the apparatus may have sufficient power to deal with disturbances.

$$I_{\eta max} = \sqrt{\frac{V_{bat} \cdot FP \cdot I_0}{(R_c + R_{bat})}} \tag{31}$$

Starting from the above equation, multiplying by Kt, we find the available torque to move the propeller:

$$J = \left(I_{\eta max} - I_0\right) \cdot K_t \tag{32}$$

Therefore, we must now find the effective voltage that is available at motor terminals

$$V_{mot} = V_{bat} - \left(I_{\eta max} \cdot (R_m + R_{bat})\right) \tag{33}$$

$$RPM = V_{mot} \cdot R_v \tag{34}$$

$$P_{mec} = RPM \cdot 2 \cdot \frac{\pi}{60} \cdot J \tag{35}$$

$$P_{ele} = V_{bat} \cdot I_{\eta max} \tag{36}$$

$$\eta_{max} = \frac{P_{mec}}{P_{ele}} \tag{37}$$

ORIENTATION OF A BODY IN THE SPACE

The orientation of a body in three-dimensional space is defined by three degrees of freedom or three linearly independent components. In order to be able to easily describe the orientation of an object relative to a reference system, it is customary to assign a new system to it, and then to analyze the spatial relationship between the two systems.

The spatial representation of the orientation of an object is defined by a global rotation matrix, which is composed of the continuous application of several successive rotations of the body.

Any reference system attached to a body whose orientation is to be described can be defined with respect to a fixed system by three angles: φ, θ, ψ, called Euler angles.

Euler's rotation theorem requires successive rotations about three axes of the fixed system, without performing two consecutive rotations on the same axis. There are altogether 12 different rotational representations.

In aeronautics the most used one is the representation of Tait-Bryan for the angles of Euler RPY (Roll: Rolling, Pitch: Inclination, Yaw: Orientation). The OUVW system (figure 46) can be oriented with respect to the OXYZ system following the following steps:

I. Turn the OUVW system at an angle ψ to the axis OZ. This action corresponds to the so-called yaw angle.

II. Turn the OUVW system an angle θ with respect to the axis OY. This action corresponds to the so-called pitch angle.

III. Turn the OUVW system at an angle φ to the axis OX. This action corresponds to the so-called roll angle.

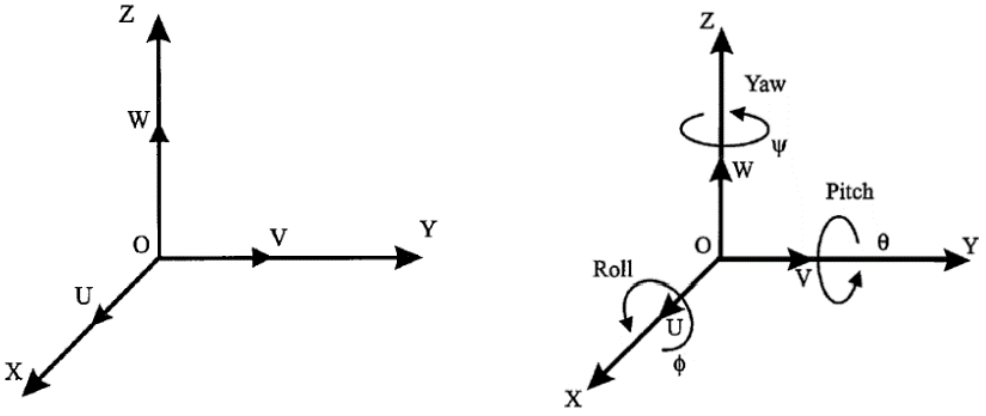

Fig 46

The global rotation matrix of the RPY representation is given by:

$$R = R_{Z\varphi}R_{Y\theta}R_{X\psi} = \begin{bmatrix} C\varphi & -S\varphi & 0 \\ S\varphi & C\varphi & 0 \\ 0 & 0 & 1 \end{bmatrix}\begin{bmatrix} C\theta & 0 & S\theta \\ 0 & 1 & 0 \\ -S\theta & 0 & C\theta \end{bmatrix}\begin{bmatrix} 1 & 0 & 0 \\ 0 & C\psi & -S\psi \\ 0 & S\psi & C\psi \end{bmatrix}$$

$$R = \begin{bmatrix} C\varphi C\theta & C\varphi S\theta S\psi - S\varphi C\psi & C\varphi S\theta C\psi + S\varphi S\psi \\ S\varphi C\theta & S\varphi S\theta S\psi - C\theta C\psi & S\varphi S\theta C\psi - S\varphi S\psi \\ -S\theta & C\theta S\psi & C\theta S\psi \end{bmatrix}$$

In Figure 46, the RPY angles of a frame are specified.

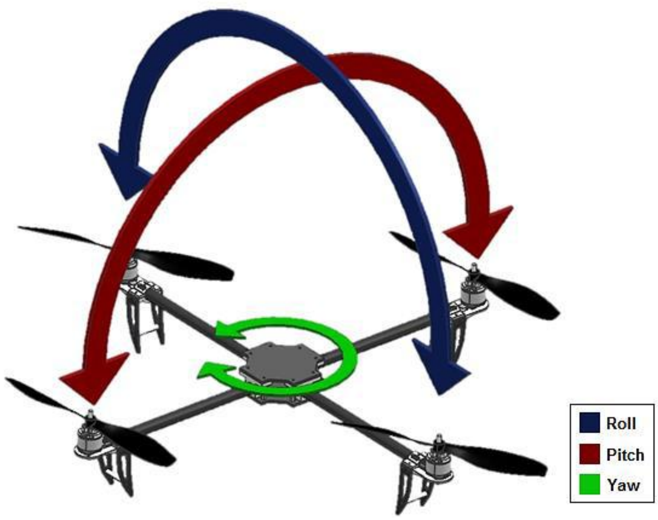

Fig 46

THEORETICAL MODEL

For the development of the theoretical model the following notation should be considered:

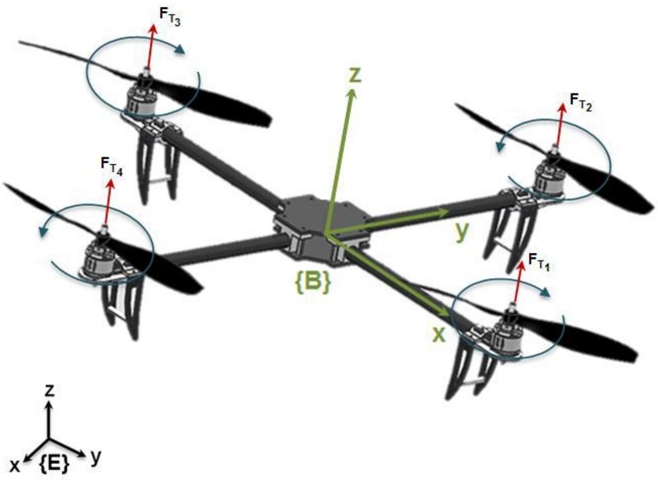

Fig 47

Where,

{E}: Fixed reference frame (ground).

{B}: Body reference frame.

F_{T_i}:Propeller thrust force i.

Aerodynamics of the quadrotor

The thrust forces and drag torques produced by the propellers are calculated by considering the blade element theory (BEM), where the thrust force and the pulling torque are expressed from the Following way:

$$F_T = C_t \rho D^4 \omega^2$$

$$Q = \frac{C_p D^5 \omega^2}{2\pi}$$

Where,

F_T: Thrust force. $[lbf]$

Q: Drag torque. $[ft.ft]$

C_t: Thrust coefficient.

C_p: Power coefficient.

ρ: Density of air. $[slugft3]$

D: Propeller diameter. $[ft]$

ω: Rotation speed of the propeller. $[rps]$

Rotational cinematic kinematics

The angular velocity of a body with reference system {B} is given by the following relation:

$$\omega = \begin{bmatrix} 1 & 0 & -sin\theta \\ 0 & cos\varphi & cos\theta sin\varphi \\ 0 & -sin\varphi & cos\theta cos\varphi \end{bmatrix} \dot{\theta}$$

Where the angular velocity vector $\mathbf{\omega} = [\omega_x, \omega_y, \omega_z]^T$ Is related to vector $\mathbf{\theta} = [\phi, \theta, \psi]^T$ In terms of the matrix of the rotating rats of the Euler angles (Jacobian matrix).

$$\begin{bmatrix} \phi \\ \theta \\ \psi \end{bmatrix} = \begin{bmatrix} 1 & 0 & -sin\theta \\ 0 & cos\phi & cos\theta sin\phi \\ 0 & -sin\varphi & cos\theta cos\varphi \end{bmatrix}^{-1} \begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix}$$

$$\begin{bmatrix} \phi \\ \theta \\ \psi \end{bmatrix} = \begin{bmatrix} 1 & sin\varphi tan\theta & cos\phi tan\theta \\ 0 & cos\phi & -sin\phi \\ 0 & \dfrac{sin\varphi}{cos\theta} & \dfrac{cos\phi}{cos\theta} \end{bmatrix} \begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix}$$

The above matrix equation represents the model of the rotational kinematics of the quadrotor with respect to the fixed reference system {E}.

Dynamics of the quadrotor

The model of the rotational dynamics of the quadrotor is expressed by the use of Euler's equation:

$$\sum T = \mathrm{I} \cdot \dot{\omega} + \omega \dot{\times} (\mathrm{I} \cdot \omega)$$

Where,

T: Vector of external torques.

$\boldsymbol{I}$: Inertia matrix.

ω: Vector of angular velocities of {B}.

To apply (63), the following considerations are assumed:

O The structure of the quadrotor behaves like a rigid body (isotropic, homogeneous and continuous structure).

O The structure is symmetric, therefore, the inertia matrix $\boldsymbol{I}$ is diagonal.

O The center of mass coincides with the origin of the body reference system {B}.

O Propellers behave like a rigid body.

O The thrust force and the pulling torque are proportional to the square of the angular velocity of the propellers, therefore, (59) and (60) can be rewritten as follows:

$$F_T = b\omega^2$$
$$Q = k\omega^2$$

Equation (63) can be written as:

$$\dot{\omega} = I^{-1}(\omega \times (I \cdot \omega) + T)$$

The Torque Vector $\mathbf{T} = [\tau_\varphi, \tau_\theta, \tau_\psi]^T$ Is composed of the moments generated by the thrust forces and the moments of drag of the propellers in each axis of rotation of the frame of reference {B}:

The torque τ_θ, is the moment generated around the x-axis by the thrust forces $FT4$ and $FT2$.

The torque τ_θ, is the momentum generated around the y-axis by the thrust forces $FT1$ and $FT3$.

The torque τ_ψ is the momentum generated around the z axis by the drag torques $Q1$, $Q2$, $Q3$ and $Q4$.

Thus, the expression for the vector of torques T is written as:

$$T = \begin{bmatrix} \tau_\varphi \\ \tau_\theta \\ \tau_\psi \end{bmatrix} = \begin{bmatrix} l(F_{T_4} - F_{T_2}) \\ l(F_{T_1} - F_{T_2}) \\ Q_1 - Q_2 + Q_3 - Q_4 \end{bmatrix}$$

Applying the equations (64) and (65) in (67), we have:

$$T = \begin{bmatrix} \tau_\varphi \\ \tau_\theta \\ \tau_\psi \end{bmatrix} = \begin{bmatrix} lb({\omega_4}^2 - {\omega_2}^2) \\ lb({\omega_1}^2 - {\omega_3}^2) \\ k({\omega_1}^2 - {\omega_2}^2 + {\omega_3}^2 - {\omega_4}^2) \end{bmatrix}$$

Where l is the distance from the center of mass of the quadrotor to the axis of the propeller.

Solving Eq. (66):

$$\begin{bmatrix}\dot{\omega}_x\\ \dot{\omega}_y\\ \dot{\omega}_z\end{bmatrix} = \begin{bmatrix}I_{xx} & 0 & 0\\ 0 & I_{yy} & 0\\ 0 & 0 & I_{zz}\end{bmatrix}^{-1}\left(-\begin{bmatrix}\omega_x\\ \omega_y\\ \omega_z\end{bmatrix}\times\left(\begin{bmatrix}I_{xx} & 0 & 0\\ 0 & I_{yy} & 0\\ 0 & 0 & I_{zz}\end{bmatrix}\begin{bmatrix}\omega_x\\ \omega_y\\ \omega_z\end{bmatrix}\right)+\begin{bmatrix}\tau_\varphi\\ \tau_\theta\\ \tau_\psi\end{bmatrix}\right)$$

$$\begin{bmatrix}\dot{\omega}_x\\ \dot{\omega}_y\\ \dot{\omega}_z\end{bmatrix} = -\begin{bmatrix}\omega_y\omega_z(I_{yy}-I_{zz}){I_{xx}}^{-1}\\ \omega_x\omega_z(I_{zz}-I_{xx}){I_{yy}}^{-1}\\ \omega_x\omega_y(I_{yy}-I_{xx}){I_{zz}}^{-1}\end{bmatrix}+\begin{bmatrix}\tau_\varphi {I_{xx}}^{-1}\\ \tau_\theta {I_{yy}}^{-1}\\ \tau_\psi {I_{zz}}^{-1}\end{bmatrix}$$

(70) represents the model of the rotational dynamics of the quadrotor.

Simplification of the model

The state vector $\mathbf{x}$ (t) takes the following form:

$$x(t) = \begin{bmatrix}\theta\\ \omega\end{bmatrix} = \begin{bmatrix}\varphi\\ \theta\\ \psi\\ \omega_x\\ \omega_y\\ \omega_z\end{bmatrix}$$

The first order differential equations are:

$$\dot{x}(t) = \begin{bmatrix}\dot{\theta}\\ \dot{\omega}\end{bmatrix}$$

Where $\dot{\mathbf{x}}$ is formed by equations (62) and (70).

$$\dot{x} = \begin{cases}\dot{\varphi} = \omega_x + (sin\varphi tan\theta)\omega_y + (cos\theta tan\theta)\omega_z\\ \dot{\theta} = (cos\varphi)\omega_y + (-sin\varphi)\omega_z\\ \dot{\psi} = \dfrac{sin\varphi}{cos\theta}\omega_y + \dfrac{cos\varphi}{sin\theta}\omega_z\\ \dot{\omega}_x = -\omega_y\omega_z(I_{yy}-I_{zz}){I_{xx}}^{-1} + \tau_\varphi {I_{xx}}^{-1}\\ \dot{\omega}_y = -\omega_x\omega_z(I_{zz}-I_{xx}){I_{yy}}^{-1} + \tau_\theta {I_{yy}}^{-1}\\ \dot{\omega}_z = \omega_x\omega_y(I_{yy}-I_{xx}){I_{zz}}^{-1} + \tau_\psi {I_{zz}}^{-1}\end{cases}$$

The model (73) can be complex for the design of controllers, so a simplified model should be obtained that describes the behavior of the aircraft in an approximate way. In this way, they will take into account considerations (Bouabdallah, Noth, & Siegwart, PID vs. LQ Control Techniques Applied to an Indoor Micro Quadrotor, 2004) and (Bresciani, 2008) to simplify the model obtained in (73).

The dynamic model of equation (70) considers the gyroscopic effect of the structure. The influence of this effect is negligible with respect to the action of the rotors, especially when considering a situation close to the stationary flight.

In stationary flight condition, the matrix of the Euler angles of rotation can be approximated to the identity matrix 3x3. Thus, equation 20 can be rewritten as:

$$w \approx \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \dot{\theta}$$

$$\begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix} \approx \begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix}$$

THE CONTROL SYSTEM OF A CUADRICOPTER

Conventional, line or sports aircraft are designed to have a self-stabilizing balance. That is, if an external disturbance tends to remove them from their level flight the natural tendency of the aircraft is to return by itself to the neutral position. This is not applicable to acrobatic aircraft or fighters where design is subtracted to increase maneuverability.

In the case of aircraft with rotating wings the situation is complicated since already the helicopter, with a single rotor, is by its own unstable topology and accurate correction systems. It is sufficient to understand that control of the tail rotor is necessary to compensate for the reaction torque produced by the main rotor if an uncontrolled yaw movement is not desired.

In the case of multirotor systems the situation is much more complex still. A multicoptero presents structural advantages but its level of instability is such that its flight and handling would be impossible of not existing a stabilization system that acted automatically on the rotating regimes of the rotors. It is what with certain aircraft is called "Fly by Wire".

This section will show, in a general way, what the control structure of a quadricopter is and what elements compose it. Since it will be necessary to use some equation, we will start by defining some of the variables that will appear later.

If the rotor angular speeds, numbered from left to right and from front to back, are designated as: ω1 ω2 ω3 ω4

The displacement angles of the quadricopter will be:

1. $alabeo$ = ϕ

2. $Cabeceo$ = θ

3. Guiñada = γ

4. Vertical thrust = L

And, therefore, the speed of movement according to these angles will be the derivative of the same with respect to time:

5. *alabeo* velocity= $d\phi\ dt = \dot{\varphi}$
6. *cabeceo* velocity = $d\theta\ dt = \theta$

7. guiñada velocity = $d\gamma\ dt = \dot{\gamma}$

8. Lift velocity=dL dt =L

One of the movements will now be considered and the result will be extrapolated to all others. Taking into account that the yaw is produced by the difference between the rotational speeds of the rotors located at the diagonal ends of the quadricopter (a configuration in X or H is considered) it will be assumed that the yaw rate can be calculated as:

$\dot{\gamma} = k((\omega 1 + \omega 3) - (\omega 2 + \omega 4))$ where k is simply a constant of proportionality. If the set of equations is presented in matrix form, and for simplicity it is assumed that all constants of proportionality are the same, the movement of the quadricopter can be expressed as:

$$\begin{bmatrix} \phi \\ \theta \\ \psi \\ \dot{L} \end{bmatrix} = \begin{bmatrix} k & -k & -k & k \\ k & k & -k & -k \\ k & -k & k & -k \\ k & k & k & k \end{bmatrix} \begin{bmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \\ \omega_4 \end{bmatrix} = [K] \begin{bmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \\ \omega_4 \end{bmatrix}$$

In order to realize the control and stabilization, what is desired to know is the speed of rotation that must be imposed on each rotor to obtain a certain velocity of displacement along the corresponding axis, the equation can be rewritten by calculating the inverse of the matrix [k] as:

$$\begin{bmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \\ \omega_4 \end{bmatrix} = [K]^{-1} \left[\begin{bmatrix} \phi \\ \theta \\ \psi \\ \dot{L} \end{bmatrix} \right]$$

This equation can already be translated graphically as follows:

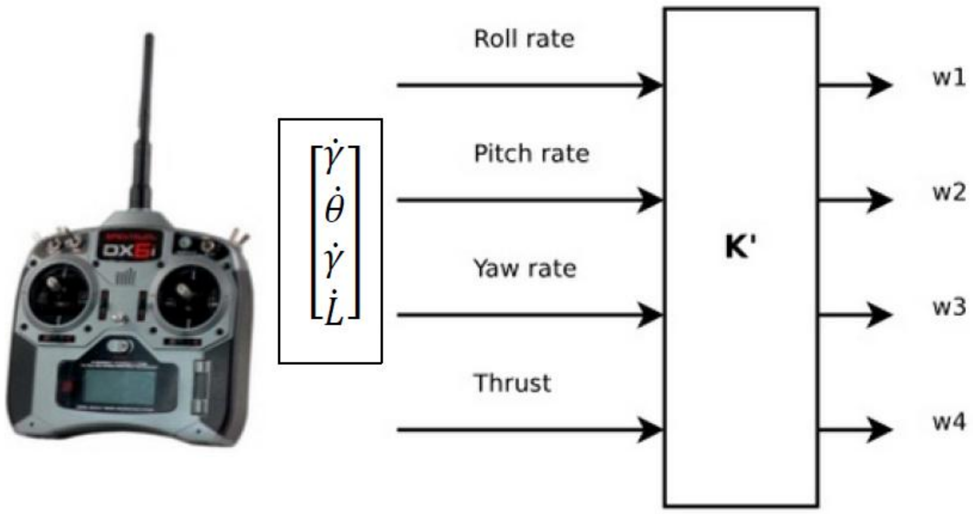

Fig 48

Once the equations have been considered, we will then proceed to develop the reasons that force the use of an advanced control system in a very intuitive way.

The overall scheme of the quadricopter's hardware is presented in the following figure. It is clear that even though all the equipment has been tried to maintain maximum symmetry, it is impossible for the 4 assemblies to behave identically: small variations in the design of the motors, in the mechanical structure, in the drive response The receiver output, etc. Make it impossible to characterize and obtain a direct and precise relationship between the command signal sent by the transmitter, which is intended to define the speed / angle of movement in each axis and the angular velocity of each of the rotor rotors.

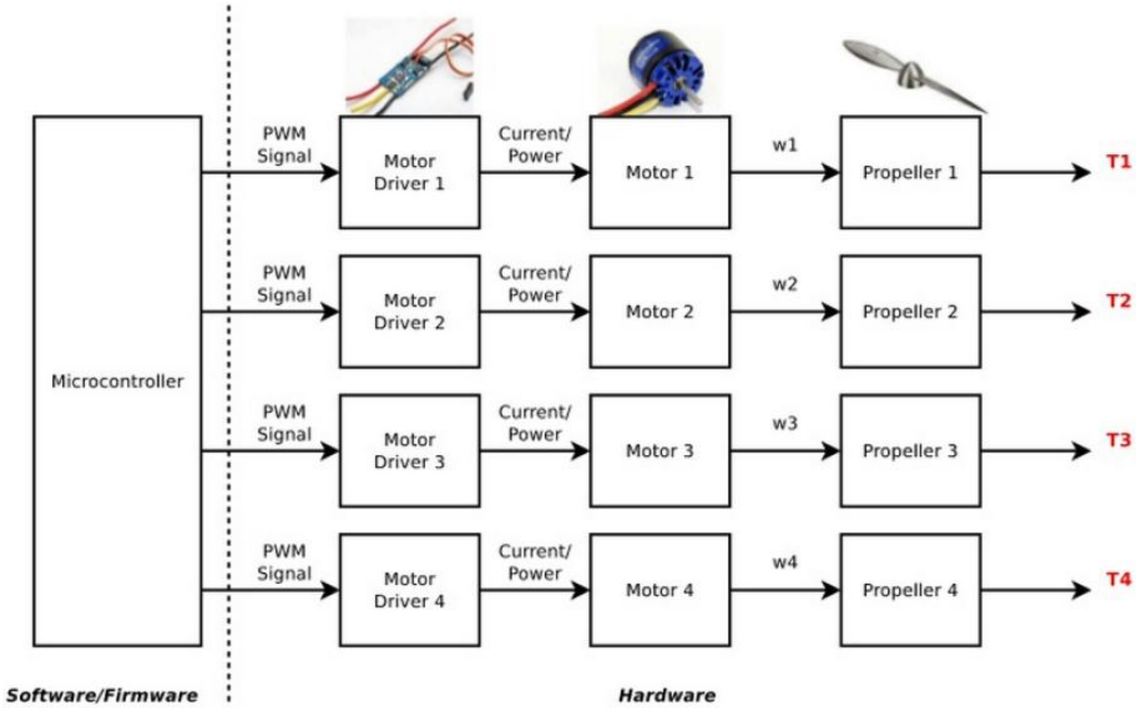

Fig 49

The solution to this problem is to use a closed-loop system. To do this, the signal obtained from the gyroscopes and solid state accelerometers present in the flight control system is obtained by obtaining the matrix of ratios of speed of movement according to the 3 axes and is compared with the desired value, indicated by the Pilot by acting on the station's controls. The difference (error) between the measured variable and the desired variable is the input to a PID controller, well known to all engineering students, and its output is the one that provides the PWM signal that is actually applied to each inverter to set the speed Of desired rotation in each rotor

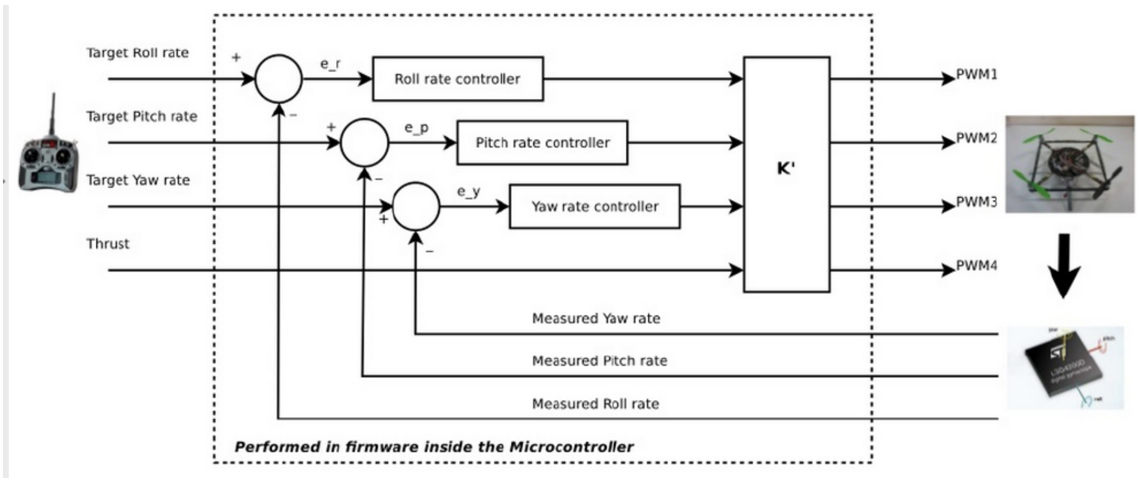

Fig 50

One would think that these control loops completely solve the problem, and therefore there is no need to further complicate the flight system algorithm. However, it is not so.

The gyroscopes measure angular velocities that, once integrated, allow to know the angle of roll, pitch, etc. Of the quadricopter. The integration made for this process is numerical and, therefore, already contains errors inherent to the mathematical calculation. In addition, all gyros have a certain "offset" with temperature. This is nothing more than a measurement error that causes them to indicate zero when they should not, and also presents the variability associated with the temperature at which the sensor is located.

On the other hand, the accelerometers measure the acceleration on the 3 axes of the object to which they are fixed. This measurement can be considered accurate when performed on a body at rest. If the object is in motion, especially if it is subjected to vibration, its measurement is not quite accurate either. Thus, if the control system is simplified to the point of Figure 50, complete stabilization will not be achieved.

The solution to solve this problem could be called "measurement fusion of the sensors" and consists in fusing the angular and acceleration measurements by introducing a predictive mathematical algorithm: usually a Kalman filter, an extended Kalman filter (EFK) or the use Of DCM (Direct Cosine Matrix) and a calculation based on quaternions, all complex mathematical processes but that can be understood intuitively from the following diagram:

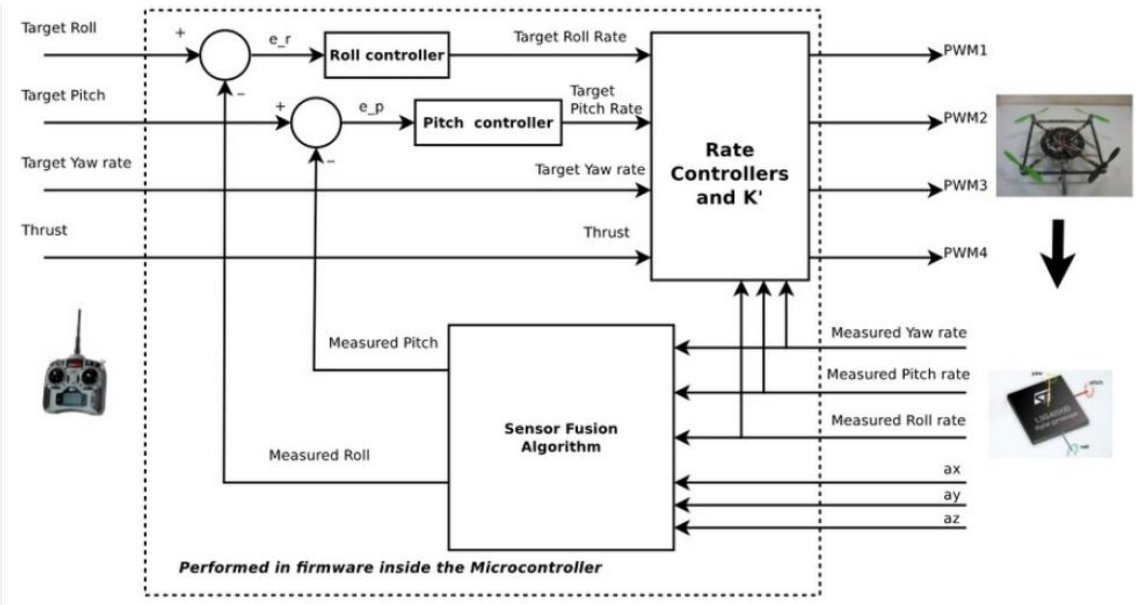

Fig 51

The control block that is called the fusion sensor is the one containing the EFK or the predictive algorithm that has been selected. The system works based on the following comparison: the variables measured by accelerometers and gyroscopes are compared with the estimation produced, for example, using Kalman Filters. These algorithms were designed in the 1960s precisely for the automatic guidance and space navigation and allow to estimate, from previous measurements the future value of the variable, for example, the angle of roll or pitch of the system. In this way an error function e (t) is defined as the difference between the measured value and the value estimated by the predictive filter.

If the controller is designed like t->infinite the error e (t)->0 will correct the deviations of the sensors due to the comparison with the predictive algorithms and the system will have adequate stabilization capacity.

Obviously, this brief explanation is only intended to help the understanding of the system and not to exhaustively analyze the control system, among other things because in order to do so it is necessary to have advanced knowledge of automatic regulation. However, it does allow an overall view of what level of complexity the control algorithms can adopt.

Although not mentioned so far, the inclusion of a GPS sensor or an altitude sensor (variometer) in the previous control scheme would be performed in a very similar way, adding the corresponding regulator and, if necessary, its corresponding estimator of State.

Plates based on the Arduino hardware platform allow the user to program the desired control algorithms. In fact, there is enough material from which it is possible to extract digital PID regulators and filters. Commercial flight control systems, which incorporate the software, may be more or less sophisticated in terms of the number of sensors they allow to enter, but in general terms they are characterized by their ease of use since only the three parameters are usually configurable Of the PID regulators.

Design of the mechanical structure

In this project has gone through different stages to reach what has been considered an optimal structure. Effort and design studies have also been carried out to assemble the basic components of a quadricopter

Strength Analysis

In order to carry out the study of efforts, the graphic design was first performed by computer using the SolidWorks program. Once each piece was faithfully drawn, they were assembled using the assembly option offered by the program. To do this, you must insert relative positional relationships between surfaces, edges or points of each piece. The result can be seen in Fig. 53

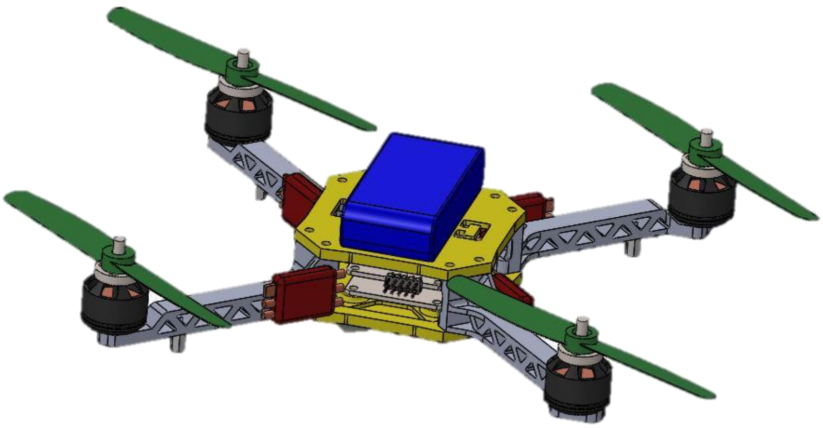

Fig 52

Next, the structure of the dron is studied, without the electronic components or motors nor propellers because Solidworks does not do the meshing correctly with all the components. The material used is ABS plastic for its economical price and because the entire structure of the drone is going to be printed in 3D. Its properties are described in the following table:

Property	Value	Units
Elastic Modulus	2000000000	N/m^2
Poisson's Ratio	0.394	N/A
Shear Modulus	318900000	N/m^2
Mass Density	1020	kg/m^3
Tensile Strength	30000000	N/m^2
Compressive Strength		N/m^2
Yield Strength		N/m^2
Thermal Expansion Coefficient		/K
Thermal Conductivity	0.2256	W/(m·K)
Specific Heat	1386	J/(kg·K)
Material Damping Ratio		N/A

A force of 2N has been applied to each axis at the ends of the arm to simulate the force exerted by the motor on the structure. The deformation produced is shown below:

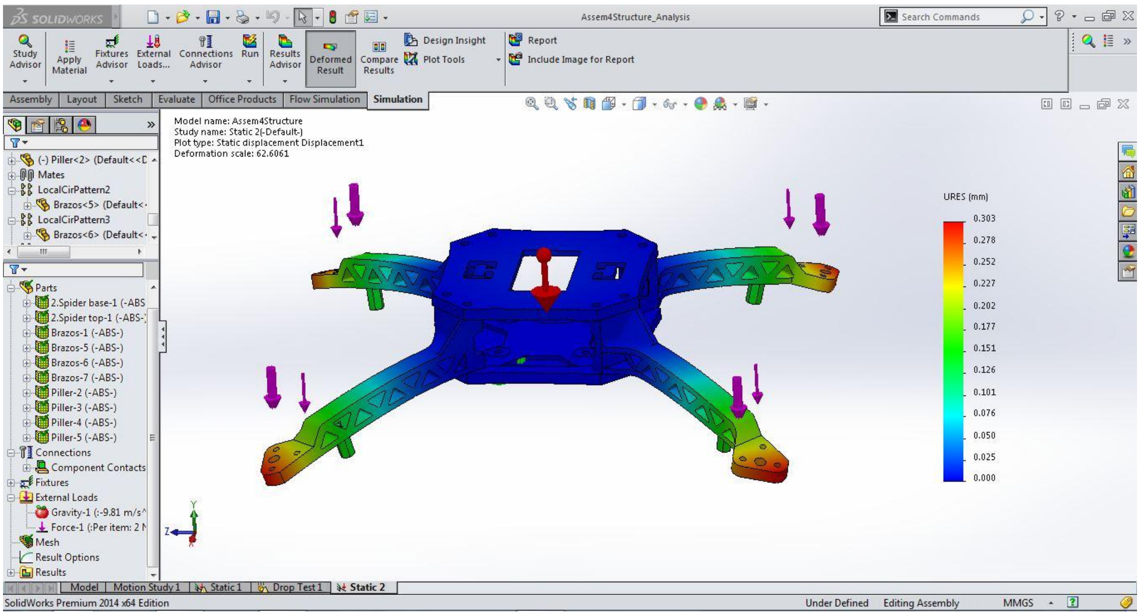

Fig 53

A maximum deformation of 0.303 mm is acceptable although we must check if the equivalent voltage of Von Misses is less than or equal to the breaking stress of the ABS.

The equivalent tension of Von Misses in the structure is as follows:

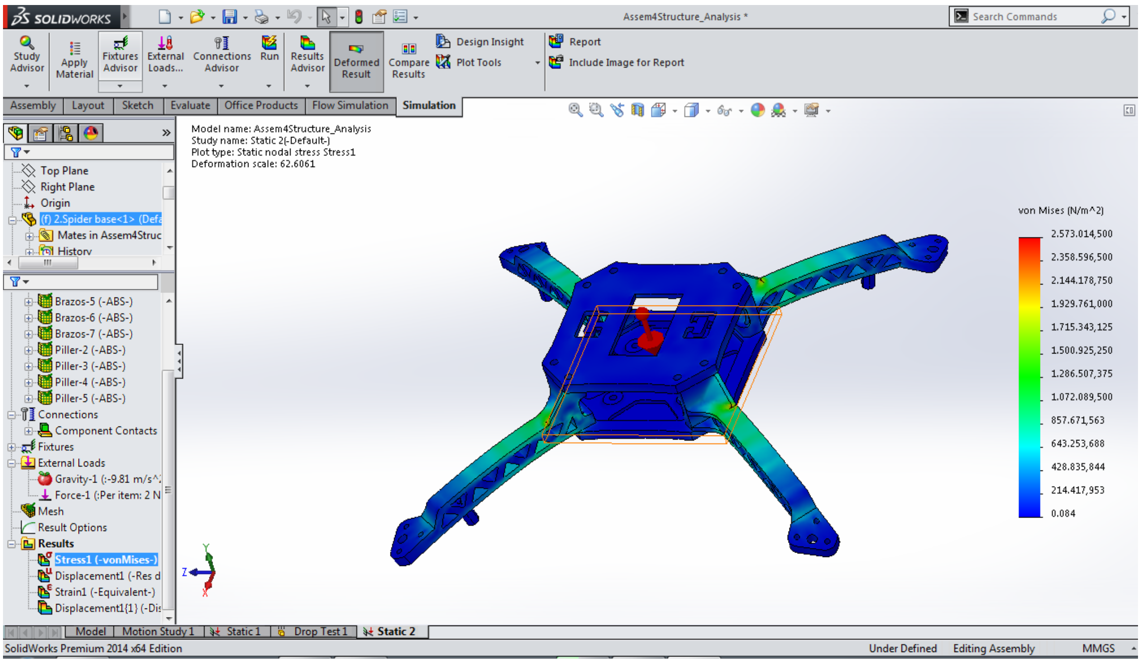

Fig 54

2573014.5 < 30000000 Therefore the structure withstands the force of the engine.

RESUMEN EN ESPAÑOL

¿Por qué?

Este tipo de plataformas son muy apropiadas para la docencia, pues integran una gran diversidad de áreas de conocimiento tales como mecánica del sólido rígido (momentos y tensores de inercia, matrices de rotación, ángulos de Euler), matemática aplicada (cuaterniones), electrónica de potencia (controladores electrónicos de velocidad), automatización (el control del vehículo), etc.

Introducción

Las aeronaves de alas giratorias con multirotores se comenzaron a diseñar, e incluso volar con éxito, a principios del siglo pasado. Fueron, sin embargo, reemplazadas en primer lugar por el autogiro, cuyo rotor principal no está motorizado y, posteriormente, por los helicópteros dada la inestabilidad inherente a las estructuras de rotor múltiple. En las siguientes figuras se puede observar el primer cuadricóptero conocido y algunas aeronaves con esta configuración de mediados del siglo 20.

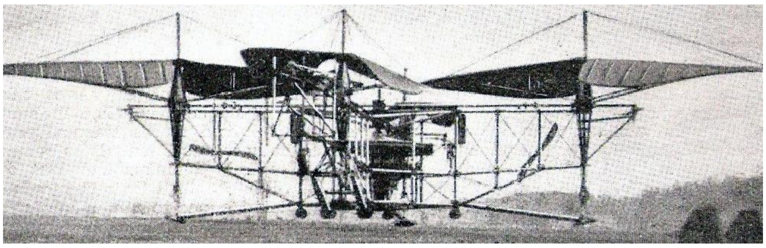

Fig 1

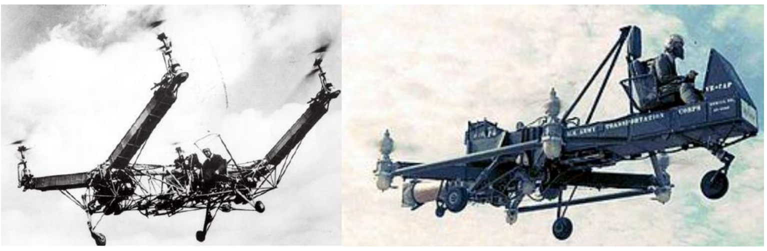

Fig 2

Si la estabilidad de las células (estructuras de las aeronaves) con múltiples alas giratorias es sensiblemente más compleja que la de los helicópteros cabría preguntarse qué ventajas aportan y el porqué de su auge actual.

En un helicóptero el rotor de cola se emplea para compensar el par de reacción (Tercera ley de Newton) producido por el movimiento del rotor principal. Variando el empuje que suministra se permite, además, el giro del helicóptero sobre el eje vertical que pasa por el centro del rotor principal (movimiento de guiñada o *yaw*). En estas condiciones la potencia consumida por el rotor de cola no se aprovecha para obtener empuje vertical, lateral o hacia adelante.

Sin embargo, es simple entender que 4 rotores con giros opuestos que compensen los pares de reacción a pares entre sí aprovecharán totalmente la potencia para conseguir empuje vertical. Desde este punto de vista la eficiencia del multicóptero es superior a la del helicóptero convencional.

Los inconvenientes derivados de la inestabilidad de las estructuras de ala giratoria múltiple quedaron resueltos con la aparición de los giróscopos de estado sólido, acelerómetros y magnetómetros que permiten integrar en componentes electrónicos y electromecánicos de muy pequeñas dimensiones las funciones de medición angular, aceleración y campo magnético terrestre. Aunque es complejo explicar el funcionar de estos dispositivos conocer de forma global sus características resulta interesante.

Los giróscopos de estado sólido presentan varias posibles configuraciones. Pueden emplear un resonador cilíndrico hecho de elementos piezoeléctricos (su deformación produce acumulación de cargas eléctricas) o bien de micro estructuras vibratorias insertas en una oblea de silicona.

La combinación de estos dispositivos permite obtener dispositivos electrónicos integrados capaces de medir ángulos de inclinación, aceleración, y campo magnético terrestre. Obteniéndose de esta forma todas las variables necesarias para determinar la posición, velocidad y rumbo de un objeto en movimiento. Los sistemas de vuelo para cuadricópteros de la plataforma hardware libre Arduino, entre otros, que inició su desarrollo en Italia en 2005, combinan todas estas funciones.

Las señales generadas por los sensores se procesan en un microprocesador que aplica varios bucles de regulación en cascada, consiguiendo de este modo que los movimientos de mando del piloto actúen combinados con las correcciones del sistema de control de vuelo. Se desarrolla así un pilotaje conocido como "*fly by wire (fbw)*" donde las acciones del piloto no actúan directamente sobre los órganos de control de la aeronave sino sobre el algoritmo de control que introduce las correcciones y compensaciones necesarias.

Los sistemas de fbw tienen su máxima representación en los cazas modernos, cuyo diseño aerodinámico es deliberadamente inestable para permitir maniobras evasivas imposibles de realizar con un pilotaje convencional. Obviamente, la ausencia del sistema de control imposibilita el vuelo de la aeronave. Podemos por tanto ya considerar que un cuadricóptero de cualquier tamaño o configuración es una aeronave de alas giratorias múltiples, gobernada por un sistema fbw que permite al piloto actuar sobre ella como lo haría sobre una aeronave convencional, añadiendo al mismo tiempo múltiples posibilidades de autoestabilización y corrección de la trayectoria y actitud de vuelo.

Cabeceo hacia adelante y atrás (avance y retroceso)

La siguiente situación corresponde a la aeronave pasando de vuelo estacionario a un cabeceo hacia delante que hace subir los rotores de cola y bajar los rotores de morro. Este efecto se consigue simplemente aumentando el empuje de los 2 rotores de cola por igual, o disminuyendo igualmente el de los dos de morro. Como se puede observar en la gráfica, las flechas rojas que indican el empuje vertical son más grandes en la parte posterior que en la anterior.

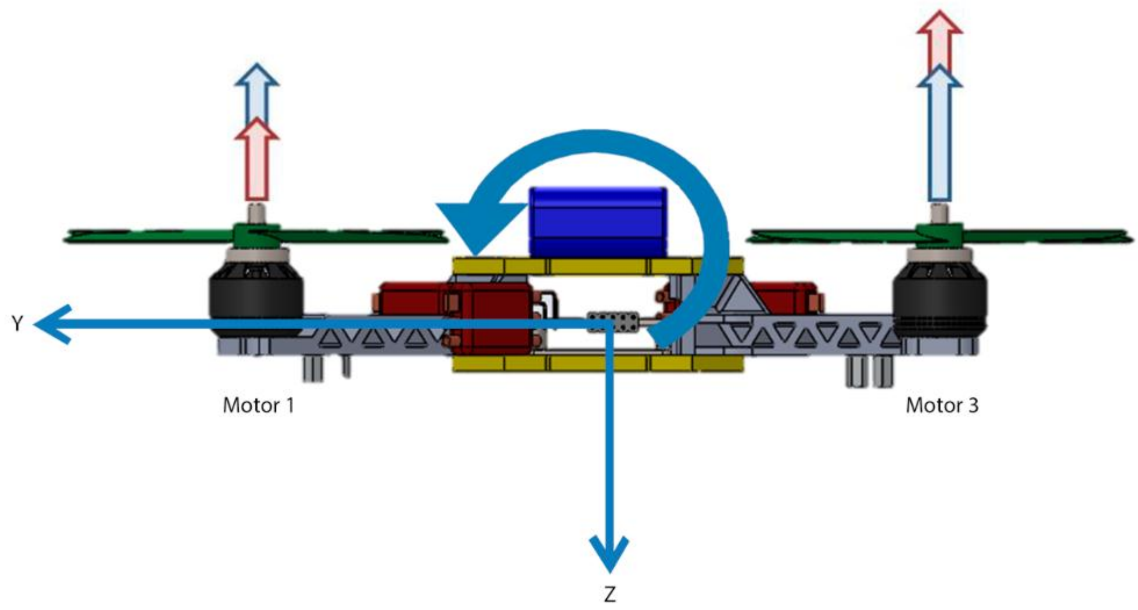

Fig 4

Este cambio en los regímenes de giro también modificará los pares de reacción. Los pares de reacción para este movimiento son intrascendentes puesto que los correspondientes a los motores traseros se compensan entre sí igualmente que los dos de los delanteros.

Es muy importante tener en cuenta que tan pronto como el cuadricóptero cabecee hacia adelante los vectores de empuje de los motores no serán perpendiculares al suelo, descomponiéndose en dos fuerzas: una vertical y otra en el sentido del cabeceo.

De este modo, siempre que se produce un cabeceo hacia adelante la aeronave comienza a avanzar en dicha dirección. El sistema de control se encargará de que en este proceso no se produzca una pérdida de altura.
El movimiento de cabeceo hacia atrás opuesto al descrito anteriormente. Debe tenerse en cuenta que al igual que ocurre durante el cabeceo hacia adelante, el cabeceo hacia atrás llevará asociado el retroceso en traslación del cuadricóptero.

Según el Teorema de la Cantidad del Movimiento se tiene que, en el eje *z*, las fuerzas han de compensar el peso, para que el dron se mantenga estable y a una cierta altura. En el eje y, en este estado, no existen componentes de las fuerzas de los motores.

Ecuación de equilibrio eje *z*:

$$\sum_{i=1}^{4} T_i = mg \tag{1}$$

Esto no introduce ninguna variación en el estado del *dron* si el diferencial que se añade en el motor 3 es el mismo que se extrae en el motor 1. En cambio, según el Teorema del Momento Cinético aplicado al centro de masas se tiene que (como aproximación, se considera que el centro de masas se encuentra en la intersección de los tres ejes):

$$\overline{GK} = \sum \overline{GP} \times \overline{F_{ext}}(P) \tag{2}$$

$$I_G \dot{\Omega} = \begin{bmatrix} 0 \\ d \\ 0 \end{bmatrix} \times \begin{bmatrix} 0 \\ 0 \\ -T_1 \end{bmatrix} + \begin{bmatrix} -d \\ 0 \\ 0 \end{bmatrix} \times \begin{bmatrix} 0 \\ 0 \\ -T_2 \end{bmatrix} + \begin{bmatrix} 0 \\ -d \\ 0 \end{bmatrix} \times \begin{bmatrix} 0 \\ 0 \\ -T_3 \end{bmatrix} + \begin{bmatrix} d \\ 0 \\ 0 \end{bmatrix} \times \begin{bmatrix} 0 \\ 0 \\ -T_4 \end{bmatrix} \tag{3}$$

$$\begin{bmatrix} I_{xx} & 0 & 0 \\ 0 & I_{yy} & 0 \\ 0 & 0 & I_{zz} \end{bmatrix} \begin{bmatrix} \ddot{\theta} \\ \ddot{\varphi} \\ \ddot{\psi} \end{bmatrix} = \begin{bmatrix} -dT_1 \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ -dT_2 \\ 0 \end{bmatrix} + \begin{bmatrix} dT_3 \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ dT_4 \\ 0 \end{bmatrix} = \begin{bmatrix} d(T_3 - T_4) \\ d(T_4 - T_2) \\ 0 \end{bmatrix} \tag{4}$$

Tal como se puede observar en la ecuación (4) los momentos en el eje *y* desaparecen al ser T4 igual que T2. Por otra parte, se crea un diferencial de momentos en el eje *x*, el cual provoca la aparición de una aceleración angular en ese eje, dando pie al movimiento anteriormente explicado. La expresión de la aceleración angular que aparece es la siguiente.

$$\ddot{\theta} = \frac{d(T_3 - T_1)}{I_{xx}} \tag{5}$$

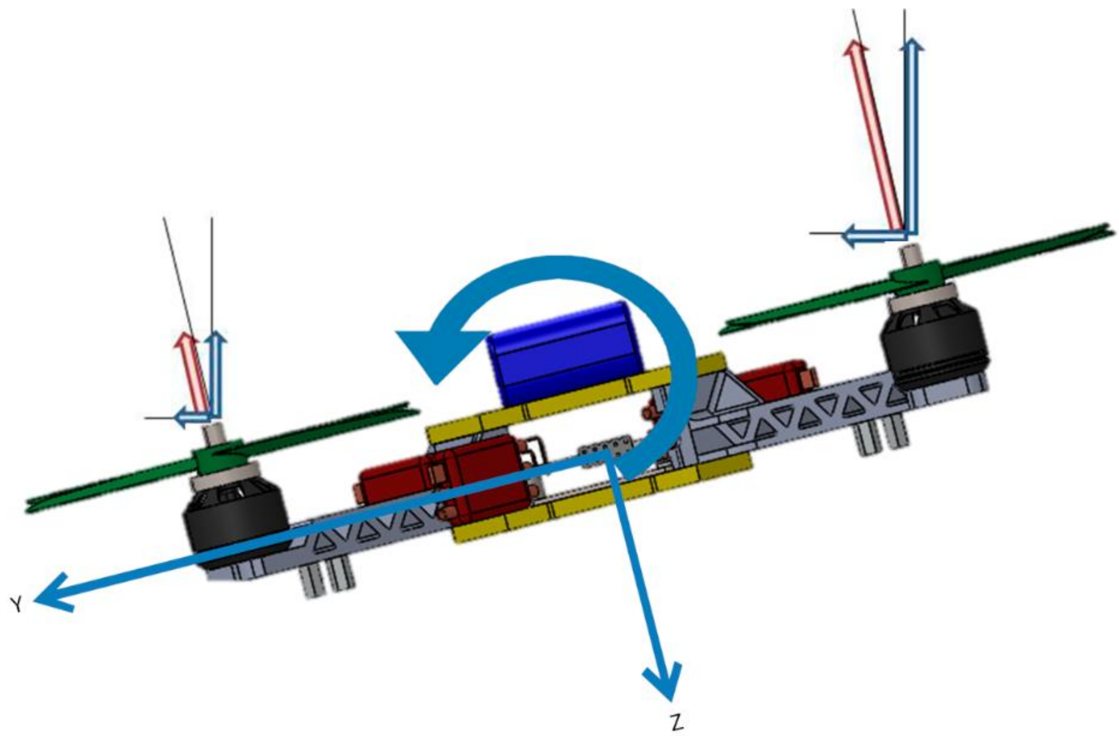

Fig 5

De este simple estudio podemos derivar parámetros de diseño ya que se comprueba cómo un brazo más largo y/o una inercia menor conseguimos aceleraciones mayores.

Alabeo a derecha e izquierda (desplazamiento lateral)

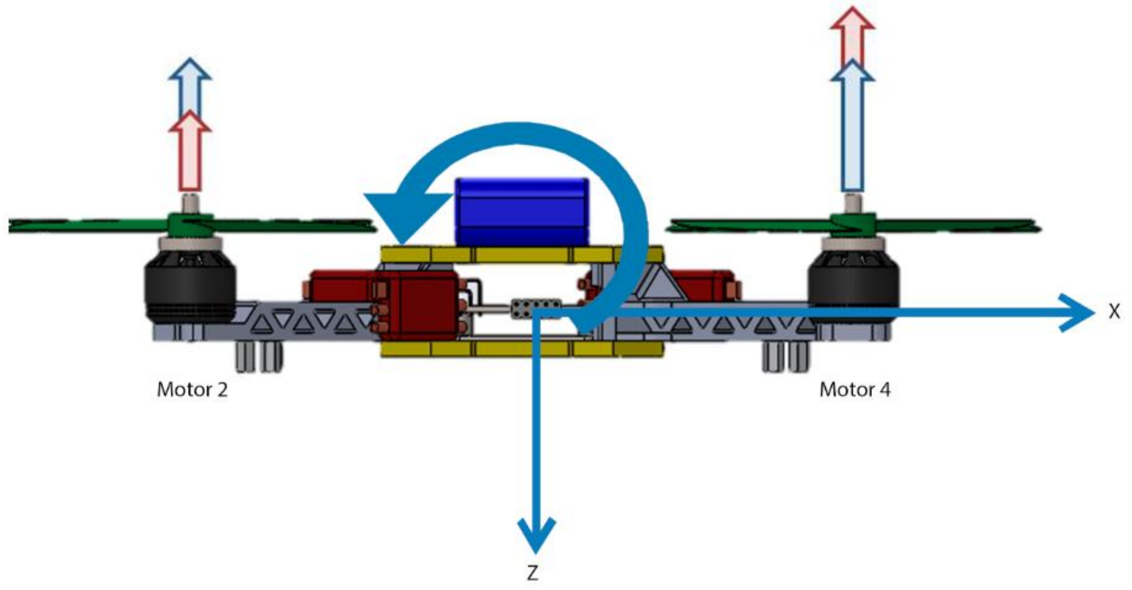

Fig 6

El mecanismo para el alabeo es idéntico al descrito para los movimientos de cabeceo. La única diferencia en este caso estriba en que el par de motores que incrementan su velocidad son los dos situados en los laterales del cuadricóptero (visto en su sentido normal de avance). De este modo, cuando se pretender alabear a la derecha la pareja de rotores del lado izquierdo incrementará su sustentación, sus pares de reacción se compensarán entre sí, y se producirá un giro sobre el eje longitudinal hacia el lado derecho. El alabeo hacia el lado izquierdo tiene lugar de manera opuesta.
Del mismo modo que en el movimiento de cabeceo el vector resultante del empuje vertical se descomponía en dos fuerzas: una para compensar el peso de la aeronave y otra hacia adelante que producía su avance, en este caso la descomposición de fuerzas dará lugar a una componente lateral que provocará, de forma análoga, el desplazamiento lateral del cuadricóptero.

En este caso también se cumple la ecuación 1 de equilibrio del TQM y, al aplicar el TMC, se llega a la ecuación número 4. Esta vez, las fuerzas que se anulan para crear momento son T1 y T3, mientras que al aparecer una diferencia entre T2 y T4 se genera un momento en el eje *y* positivo cuya aceleración angular queda definida por la ecuación 6:

$$\ddot{\varphi} = \frac{d(T_4 - T_2)}{I_{yy}} \tag{6}$$

De igual manera, aparece una componente horizontal que genera el movimiento de traslación en el sentido en el que el dron se ha inclinado.

Guiñada en vuelo estacionario nivelado (giro sobre sí mismo)

Al igual que en un helicóptero es necesario un rotor de cola para contrarrestar el par ejercido por las palas, el mismo problema ocurre en un multicoptero y, por ello, existen varias formas de lidiar con este problema.

Lo más corriente en un multicóptero es tener un numero par de hélices, por lo que lo más común para controlar la guiñada es hacer girar la mitad de los motores en sentido contrario a la otra mitad, de esta forma los pares de reacción producidos por las hélices se contrarrestan entre sí. El inconveniente de este método es la necesidad de contar con dos tipos de hélices. Debido a que las hélices tienen un perfil aerodinámico concreto, no basta simplemente con poner las hélices del revés pues, aunque se generaría empuje, no sería suficiente.

Otro método, consiste en girar todos los motores en el mismo sentido y generar contrapar con alguna característica de diseño. El principal método consiste en inclinar todos los rotores respecto de la vertical para contrarrestar el par producido por las hélices. De esta forma, al igual que en el caso anterior, podemos controlar la guiñada variando la velocidad de dos de los cuatro rotores (en el caso del cuadricóptero).

La alternativa, manteniendo las cuatro hélices rotando en la misma dirección consiste en aplicar un método similar al introducido anteriormente, donde a uno de los rotores se le da un grado de libertad de giro perpendicular al brazo. Este grado de libertad es controlado por un servomotor unido al control de vuelo y, según la rotación del motor, se consigue una guiñada en un sentido u otro. Cabe destacar que la posición de reposo del motor no es paralela con el resto de motores, sino que esta rotada para evitar una guiñada indeseada. Esta forma de controlar la guiñada es utilizada especialmente en tri-rotores, donde se hace necesaria algo más de complejidad mecánica para poder controlar la guiñada.

La última alternativa consiste en colocar superficies de control a la salida que redireccionen el flujo de aire saliente de la hélice y proporcionen un contrapar. La variación del ángulo de estas superficies conseguirá el movimiento de guiñada.

En nuestro caso, se utilizará el primer método descrito ya que el objetivo buscado es la simplificación del diseño tanto mecánico como aerodinámico.

Respecto del movimiento de guiñada de los cuadricópteros es importante señalar que, en términos generales, es menos eficiente que el de un helicóptero. Es decir, que su giro sobre el el eje vertical suele ser más lento. La explicación a este fenómeno es clara: mientras que en un helicóptero el rotor de cola se encarga exclusivamente del movimiento de giñada en un cuadricóptero no se puede obtener un par de rotación de la misma magnitud ya que la descompensación de los empujes de los motores tiene que mantenerse dentro de los límites necesarios para mantener la aeronave nivelada.

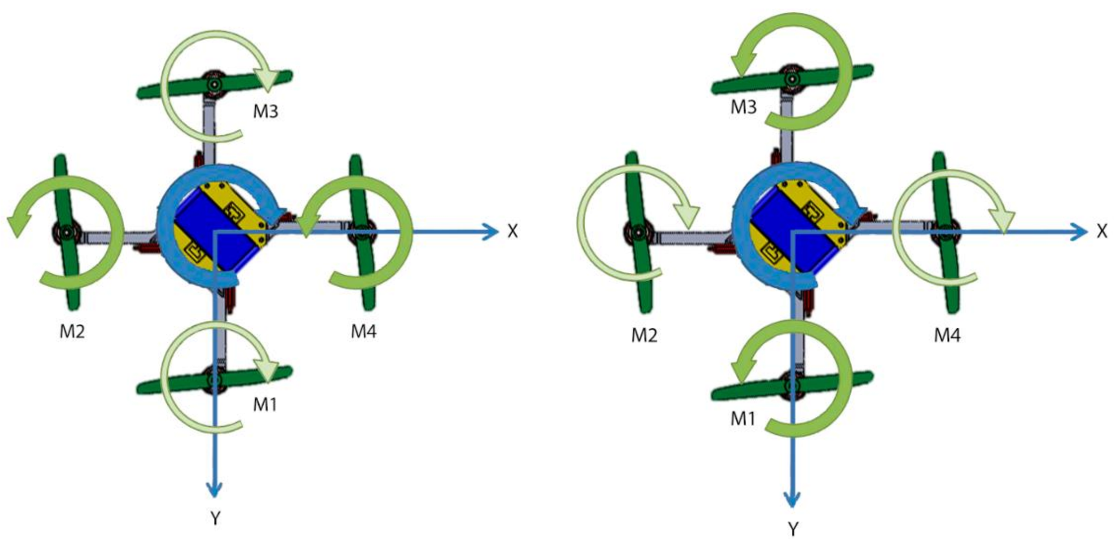

Fig 8

El momento que induce este movimiento se puede expresar según la siguiente ecuación:

$$M_\psi = \sum_{i=1}^{4} \tau_{mi} = \sum_{i=1}^{4} (I_{zm} \cdot \dot{\omega}_i - \tau_{dragi}) \qquad (9)$$

El momento de yaw se produce, tal como se ha comentado antes, al sumar los cuatro momentos rotacionales de los cuatro motores. Al girar dos en un sentido y los otros dos en otro sentido, en régimen estacionario se equilibran y mantienen el dron estable en cuanto al movimiento de yaw.

En cambio, al aumentar la velocidad de giro de los motores pares y disminuir de la misma manera la de los motores impares, se crea dicho momento en el mismo sentido que los motores cuya velocidad de giro se disminuye. Esto sucede con tal de conservar la cantidad de movimiento. En este caso, el *dron* se orientaría en sentido anti horario si se considera el eje *z* positivo cuando apunta hacia el suelo u horario si se observan las imágenes.

Existen algunas configuraciones especiales de equipos multirotor donde se emplean números impares de rotores para obtener una mayor agilidad para este movimiento. En cualquier caso, para aplicaciones industriales no se precisa una elevada velocidad para la guiñada y ese tipo de configuración suele estar diseñado para aeromodelos de carácter acrobático donde se incluyen incluso hélices de paso variable gobernadas por servos.

La velocidad máxima del aparato vendrá determinada por dos factores; la sustentación del aparato, y la resistencia del aire. Debido a la complejidad del análisis aerodinámico del aparato, no se determinará la forma analítica la resistencia aerodinámica del mismo.

También podemos determinar la inclinación máxima que puede mantener el aparato manteniendo la altitud y por tanto su aceleración lineal máxima.

$$\theta_{max} = \cos^{-1}\left(\frac{M_{tot} \cdot g}{F_{max}}\right) \tag{10}$$

Siendo $F_{max} = F_1 + F_2 + F_3 + F_4$

Conocido el ángulo podremos determinar ahora su aceleración lineal máxima.

$$a_{max} = \frac{F_{max} \cdot \sin\theta_{max}}{M_{tot}} \tag{11}$$

Parametros eléctricos

El esquema eléctrico del aparato es el siguiente:

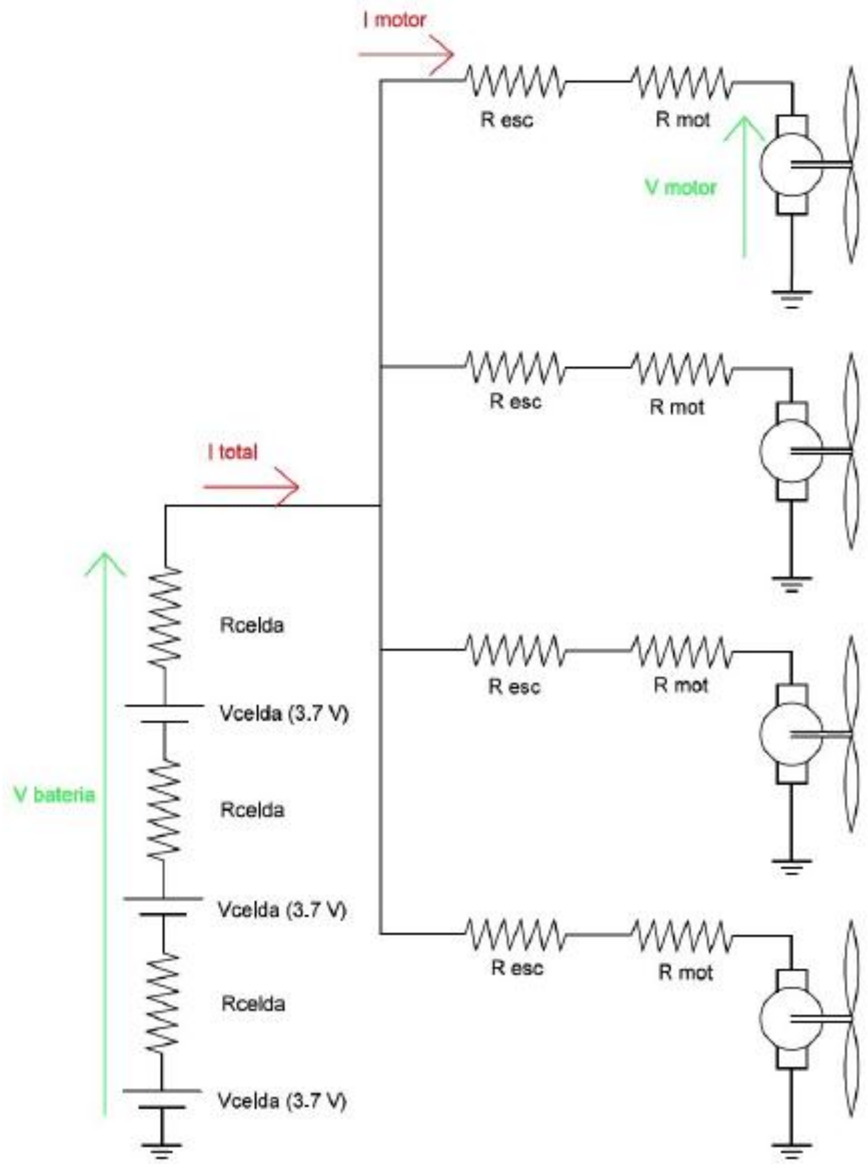

Fig 44

Actualmente los motores BLDC (Brushless Direct Current) de radiocontrol se clasifican principalmente atendiendo al parámetro Kv, siendo:

$$K_v = \frac{RPM}{Voltios} \tag{15}$$

Sabemos que:

$$K_t = \frac{30}{K_v \cdot \pi} \tag{16}$$

De estas forma obtnemos el parámetro Kt:

$$K_t = \frac{Par}{Amperios} \tag{17}$$

Conociendo las velocidades angular y la fuerza necesaria podemos ahora relacionarlos con la tensión y la corriente de cada motor:

$$\frac{RPM}{K_v} = V_e \tag{18}$$

$$\frac{J}{K_t} = I_e \tag{19}$$

Donde V_e es la tension de entrada e I_e es la corriente. Sin embargo, deberemos considerar la resistencia de los conectores y cables a la entrada al igual que la resistencia de los conectores por tanto quedando las ecuaciones de la siguiente manera, siendo R_c la resistencia de conectores y cables:

$$\frac{RPM}{K_v} = (V_e - R_c \cdot I) \tag{20}$$

En el término R_c también se incluye la resistencia interna de la batería. En general, las baterias de litio, ven determinada su capacidad de descarga máxima debido a la resistencia interna. Sin embargo, no es un dato típicamente proporcionado por los fabricantes. No existe un estándar por el que clasificar la calidad de las baterías de aeromodelismo y las diferencias entre baterías de distintos precios no están claras.

Debemos tener en cuenta la corriente que consume el motor sin carga, que representa la corriente de Vacio I_0, por tanto, la ecuación anterior queda:

$$J = K_t I_e - K_t I_0 \tag{21}$$

Despejando:

$$\frac{J + K_t I_0}{K_t} = I_e \tag{22}$$

Podemos calcular la potencia eléctrica de entrada como:

$$P_{e,entrada} = I_e \cdot V_e \tag{23}$$

Sistema AntiSpark

A continuación, se detalla el diseño de un sistema encargado de evitar las indeseables chispas al conectar el sistema de baterías. Debido al alto nivel de voltaje y carga de las baterías, cuando éstas se conectan para dar potencia a los motores se produce un chispazo que puede llegar a dañar los conectores y ser peligroso para el usuario de la aeronave. La chispa se produce debido a que el voltaje de las baterías supera el voltaje de ruptura del espacio de aire entre los dos conectores. La forma de evitar este indeseado fenómeno es realizar una carga previa de los condensadores de entrada del circuito electrónico que se desea alimentar, los variadores en el caso estudiado. Esto aumentará el voltaje de ruptura y se eliminará el problema.

Por lo que se debe diseñar un sistema que permita la carga previa de los condensadores de los variadores, antes de realizar la conexión total de potencia. Se decide la solución de hacer circular una pequeña corriente a través de una resistencia durante un corto espacio de tiempo para cargar los condensadores y, a continuación, desviar el flujo de corriente por otro circuito que ofrezca menos impedancia para alimentar el circuito.

Esto se consigue mediante la inclusión de un sistema de transistor más condensador. En la siguiente figura se puede observar el circuito propuesto.

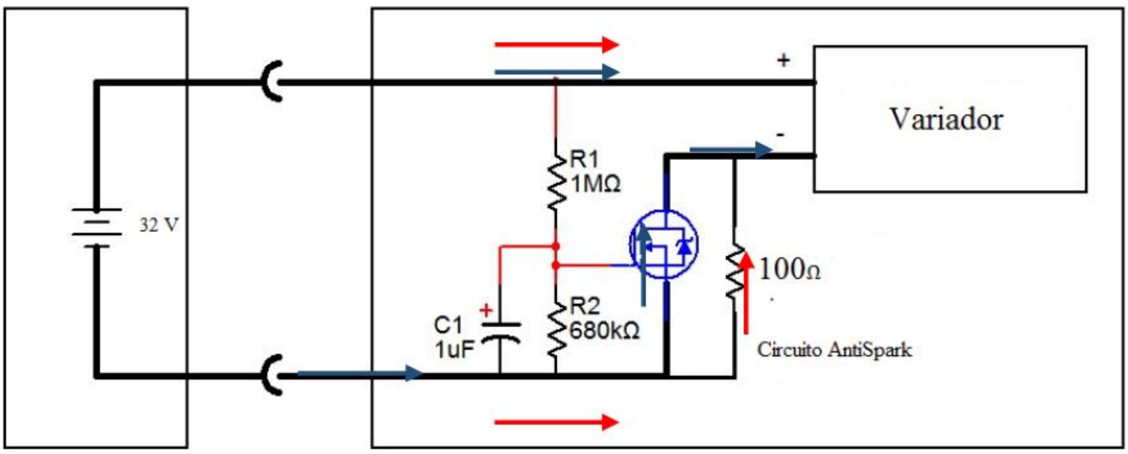

Fig 45

En un primer momento de funcionamiento el transistor está abierto por lo que la corriente circula según indican las flechas rojas, a través de la resistencia de 100 Ω que proveerá una corriente limitada para realizar la carga de los condensadores del variador. El transistor se cierra transcurrido el tiempo de carga del condensador del circuito que dependerá tanto de la capacidad del mismo como de las resistencias involucradas en el esquema, según la siguiente fórmula:

$$V(t) = V_f \left(1 - e^{\frac{-t}{RC}}\right) \tag{45}$$

Siendo:

$V(t)$: La tensión en el condensador

V_f: La tensión entre las placas del condensador

t: El tiempo de carga del condensador

R: Resistencia del circuito en Ohmnios

C: Capacitancia del condensador

Los valores elegidos de los componentes del circuito se obtienen de tal manera para que el tiempo de carga del condensador del mismo, sea suficiente para que los condensadores de los variadores se carguen a través de la resistencia. Para conocer este valor de tiempo basta con resolver las ecuaciones propias del condensador.
La tensión entre las placas del condensador se obtiene resolviendo la malla por lo que:

$$I_f = \frac{V_{bat}}{R_1 - R_2} = \frac{32\,V}{680\,K\Omega + 1M\Omega} = 1.9048 \cdot 10^{-5}$$

$$V_f = I_f \cdot R_2 = 1.9048 \cdot 10^{-5} \cdot 1M\Omega = 19.05\,V$$

El valor de *V(t)* viene dado por la tensión del circuito en ese punto, es decir, el voltaje necesario a la entrada del transistor para que éste cierre el circuito. En el caso del transistor utilizado este valor corresponde a 3 Voltios.
Por lo que:

$$t = -(R_1 + R_2) \cdot C \cdot \ln\left(1 - \frac{V(t)}{V_f}\right) = -1.68M\Omega \cdot 1\mu F \cdot ln\left(1 - \frac{3\,V}{19.04\,V}\right) = 0.28s$$

Valor de tiempo más que suficiente para que se produzca la carga de los variadores previa al cierre del circuito principal de potencia. Una vez el transistor funciona como circuito cerrado la corriente circulará por donde indican las flechas azules del esquema de la figura. En este caso se observa que la energía circulará a través del transistor cuya impedancia debe ser la menor posible para evitar pérdidas por disipación y maximizar la eficiencia de las baterías.

Otros parámetros:

Eficiencia del motor:

$$\eta_{mot} = \frac{P_{mec}}{P_{ele}} \tag{46}$$

Duracion de la batería:

$$Duración = \frac{I_e}{\frac{Capacidad}{10000}} \tag{47}$$

Estudio de esfuerzos

Para realizar el estudio de esfuerzos primeramente se realizó el diseño gráfico por ordenador mediante el programa SolidWorks. Una vez se dibujó con fidelidad cada una de las piezas, se ensamblaron mediante la opción de ensamblaje que ofrece dicho programa. Para ello, hay que insertar unas relaciones de posición relativas entre superficies, aristas o puntos de cada pieza. El resultado se puede observar en la Fig. 53

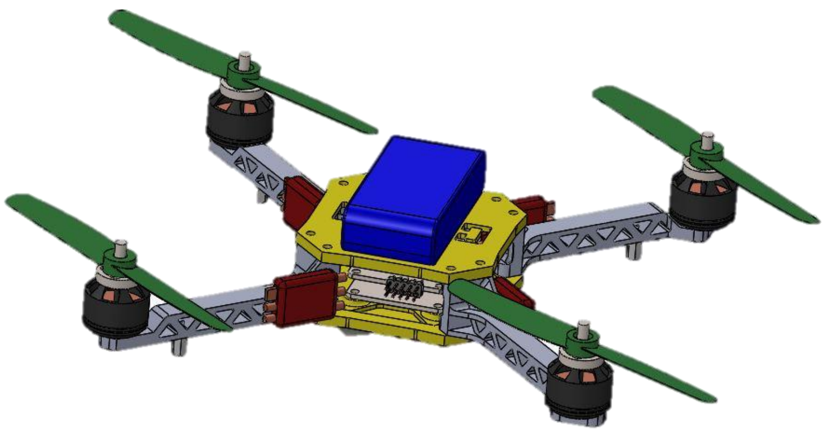

Fig 53

A continuación, se estudia la estructura del dron, sin lo componentes electrónicos ni motores ni hélices debido a que Solidworks no hace el mallado correctamente con todos los componentes. El material empleado es plástico ABS por su precio económico y porque toda la estructura del drone va a estar impresa en 3D. Sus propiedades vienen descritas en la siguiente tabla:

Property	Value	Units
Elastic Modulus	2000000000	N/m^2
Poisson's Ratio	0.394	N/A
Shear Modulus	318900000	N/m^2
Mass Density	1020	kg/m^3
Tensile Strength	30000000	N/m^2
Compressive Strength		N/m^2
Yield Strength		N/m^2
Thermal Expansion Coefficient		/K
Thermal Conductivity	0.2256	W/(m·K)
Specific Heat	1386	J/(kg·K)
Material Damping Ratio		N/A

Se ha aplicado una fuerza de 2N en cada eje de los extremos del brazo para simular la fuerza ejercida del motor sobre la estructura. A continuación, se muestra la deformación producida:

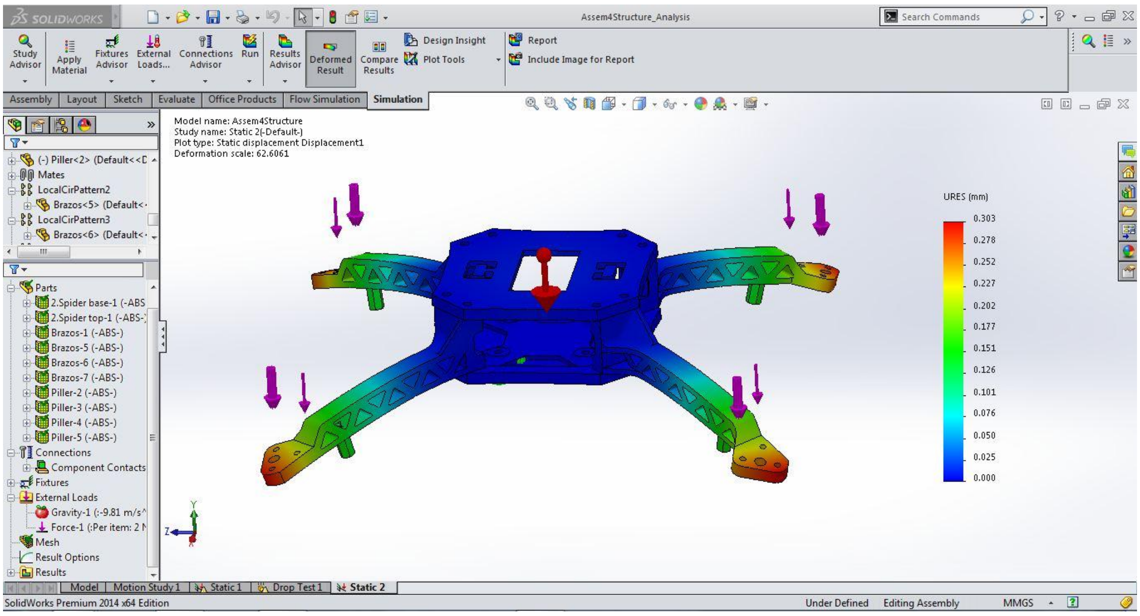

Fig 54

Una deformación máxima de 0.303 mm es aceptable, aunque debemos comprobar si la tensión equivalente de Von Misses es menor o igual que la tensión de rotura del ABS.

La tensión equivalente de Von Misses en la estructura es la siguiente:

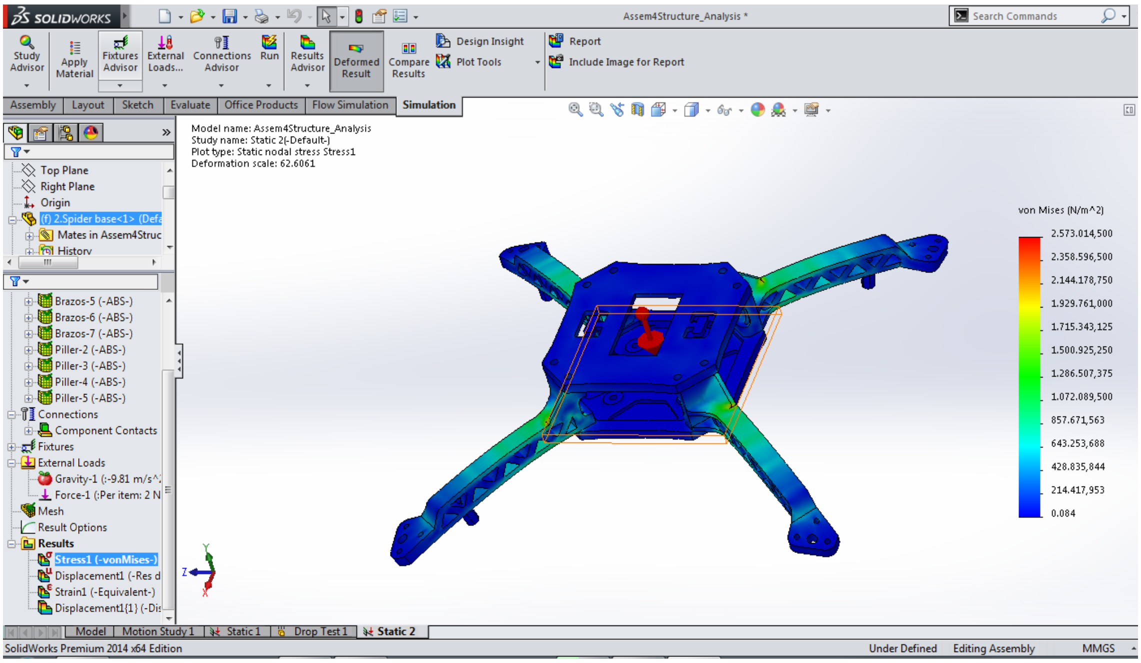

Fig 55

2573014.5 < 30000000 Por lo tanto la estructura aguanta la fuerza del motor, es decir, el dron diseñado puede pasar a la fase de producción que, por motivos económicos no se pudo realizar en este proyecto.

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