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POWERPLANT SYSTEM DESIGN FOR UNMANNED TRICOPTER

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Abstract: In this article components of powerplant system for an electrically powered unmanned tricopter is designed in order obtain safe and performable autonomous tricopter flight. Electricity is the most environmental friendly energy form. Components used in propulsion systems for a unique tricopter with rotating wing unmanned aerial vehicle that use it as electrical energy source are: propellers, motors, ESC's (i.e Engine Speed Controller) and battery. The battery stores electricity. The storage capacity of the battery is most important factor which affecting the tricopter's flying time but the more battery storage capacity as well as more battery weight. If the weight of tricopter is excessive, more thrust must be produced so that the movement capacity not restricted. ESC adjusts the rotation speed of the motor according to the signals received from the rc receiver and the thrust power of the tricopter is adjusted. Motors are the main factor in generating thrust power. The torque of the motor is also important parameter as much as the motor rotation speed (RPM) so that the desired thrust power can be generated. Powerless or low torque motor can heat up and break down when turn the propeller. The last component of thrust system is propeller moves the air. Propeller which is connected the moving part of motor, pushes the air from leading edge of the propeller to trailing edge for generate a thrust power. The most important factors affecting thrust power are length, pitch and RPM of propeller and forward flight speed. Other factors are like air temperature, air pressure, propeller's angle of attack and density of air.

Keywords**:** UAV, ESC, electric motor, propeller

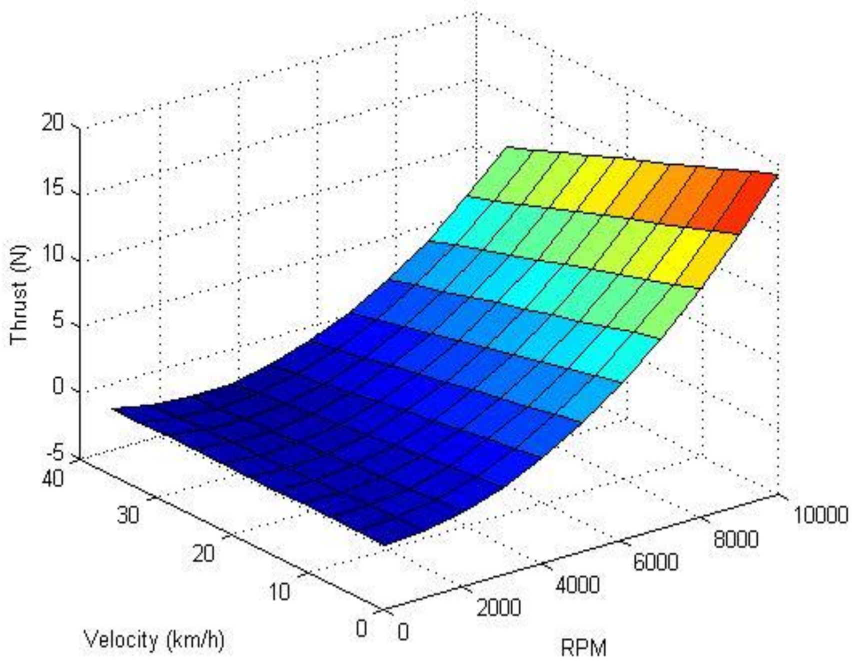

Figure 1. Effect of velocity and RPM on thrust of propeller

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Introduction

The Unmanned Aerial Vehicles (UAV) is the flying vehicles with autonomous pilot. For the preceding four and five decades Unmanned Air Vehicles (UAVs) have been widely benefited for military operations and also in commercial applications due to their many advantages with respect to the manned vehicles. Some of these advantages are having lower cost in manufacturing and operating, elasticity in configuration depending on customer demand and they are not risking the pilot’s life on difficult missions. UAVs have been used in aerial photography (e.g. film and video), agriculture (i.e. crop monitoring and spraying), coast guarding (e.g. coastline and see-lane), conservation (e.g. pollution and land monitoring), customs and excise (e.g. surveillance for illegal imports), electricity companies (e.g. powerline inspection), fire services and forestry (e.g. fire detection and incident control), fisheries (i.e. fisheries protection), gas and oil supply companies (e.g. land survey and pipeline security) etc. with civilian purposes. They have also been applied to military tasks. For example, they have been used for navy (e.g. shadowing enemy fleets, decoying missiles by the emission of artificial signatures, protection of ports from offshore attack), army (e.g. reconnaissance, surveillance of enemy activity, monitoring of nuclear, biological or chemical NBC contamination, location and destruction of land mines) and air force (e.g. long-range, high-altitude surveillance, radar system jamming and destruction, airfield base security, airfield damage assessment). For more UAV applications, Austin R., 2010 can be examined. Many scientific research on UAV design and control have been also conducted recently (e.g. Grabowski et al. 2006; Ding, Liu and Hsiao; 2013; Drak et al. 2014; Filippis, Guglieri, Quagliotti, 2014; Higashino and Funaki, 2013; Wilburn et al. 2013; Hadi et al. 2014).

Especially; small scale unmanned aerial vehicles with vertical take-off and landing (VTOL) capabilities have produced for different target. The VTOL UAVs are generally made with several motor and propeller combination and that’s why these VTOL UAVs are known as multicopter or multirotor. The VTOL UAV’s can be used in small areas and quickly. The UAV’s could be sudden directional turns and avoid a sudden collision. For accomplishment these requirements, a multi-rotor UAV is the best solution. Various types of multi-rotor have been produced like bi-copter, tricopter, quadcopter vs. In this article our aim is understand to tricopters powerplant system. The most important advantages of tricopter is made from less motor than quadcopter and other multi-rotor and more stable than bi-copter. As compared other multi-rotor; tricopter has more flight time on account of the fact that lighter than other multi-rotor.

Method

The popular thrust generation method is drive a propeller. The total thrust must be least twice than weight of tricopters. Tricopters weight includes frame, flight control card, power distribution card, wires, motors, ESCs, battery and another useful load like gimbal or cargo load. Sum of total weight is necessary for calculation of required thrust force. Another important factor is the purpose of use the tricopter. Tricopter, which will use in race, would be design for speed and then ratio of thrust-weight more than 2:1 like 8:1 even 10:1 or more. But excessively high trust-weight ratio cause hard control of tricopter. On the contrary, if the thrust which produced by propeller isn’t enough, tricopter has not stable fly, hard to control during hovering and it may not even take off when total propulsion of propeller less than total weight of tricopter. For example, if we want design a tricopter which weights 1200g, the total thrust at 100% throttle should be least 2400gr or 800gr per motor.

One of the most important point of design tricopter is choosing the right propulsion system. Knowing of tricopter size, give us a maximum propeller size that can be used. By using this information the necessary thrust can be calculate.

Propellers

Propellers generate thrust by spinning and moving air. The more air it can move, the more thrust will generate. Multirotor propellers are one type of rotated wing which mounted vertically. Propellers are driven by motor to pull-push air for produce a propulsion. All propellers are designed two measurement, both given by inches.

Figure 1. Illustration of propeller and Its diameter

There are propellers of different length and pitch. For example 11X5.5 (sometimes 1155) propellers are 11 inch long and has a pitch of 5.5 inch or 5x3x3 (sometimes 5030×3) means 3-blade 5″ long propeller that has a pitch of 3 inch. The pitch measurement of propeller indicates how far along on a one tour of propeller so the higher pitch value, the faster propeller or the more thrust.

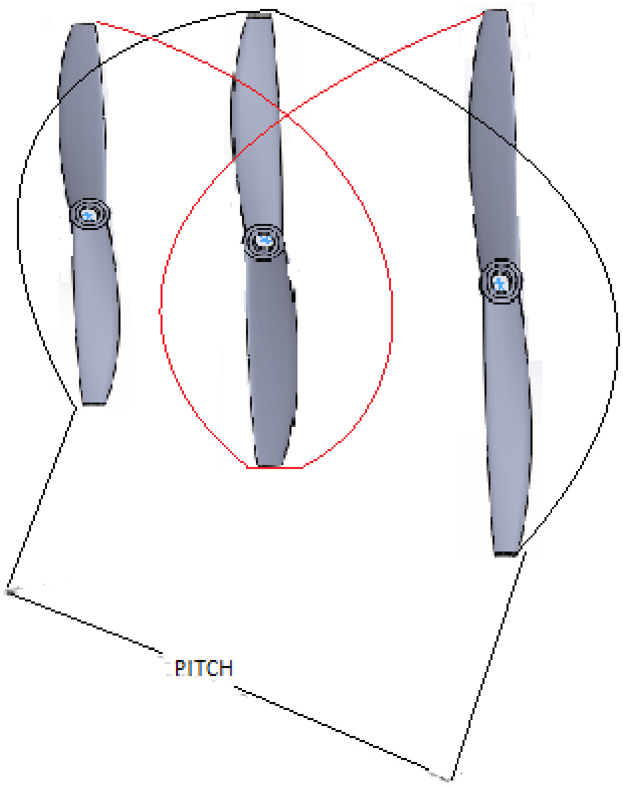

Figure 2. Illustration of propeller pitch

The thrust produced by a propeller depends on density of air, RPM of propeller, diameter, shape and area of the blades and pitch. A propeller efficiency relates to the angle of attack. The efficiency is a ratio of the output power to the input power. The angle of attack is affected by the relative velocity, so a propeller will have different efficiency at different motor speeds. The efficiency is also greatly affected by the leading edge of the propeller blade, and it is very important. Leading edge of blade must as smooth as possible. A higher pitch propeller moves greater amount of air, which could create turbulence and cause more prop wash. It generates more thrust in the expense of higher current draw, but giving you higher top speed. A larger diameter propeller reduces the motor's RPM because of drag.

Propellers are either designed to rotate clockwise (CW) or counter-clockwise (CCW). It is important to know which part of the propeller is intended to face upwards (the top surface is curved outward). If the design of your multicopter inverts some of the motors be sure to change the orientation of the propellers so the thrust is still downwards. The top of the propeller should always face the sky.

Propellers can be made of different materials, plastic, carbon fiber, wood etc. Each type of material gives unique features, for example carbon fiber and wooden propeller are best known for their smooth performance, certain plastic compound are very durable. In electric motor, propeller selection is more critical because wrong propeller can cause broke the propeller or fire the ESC or battery.

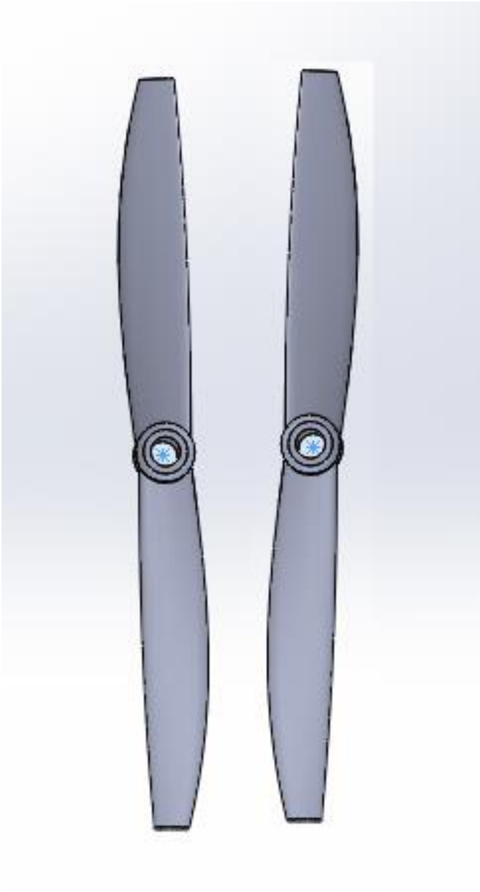

Figure 3. Illustration of propellers rotation (CW-CCW)

Motors

The motor will have a huge impact on the payload or maximum load which our UAV can support, as well as the flight time. We strongly recommend that using the same motor and propeller in three locations. Note that even if a pair of motors are the same model and the same production their speeds may be different, because of the electronic speed controller or flight control card.

Brushless motors, have become very popular with "Electro Flight" unmanned aerial vehicle like tricopter because of their efficiency, power, longevity and light weight in comparison to traditional brushed motors. Brushed motors spin the coil inside a case with fixed magnets mounted around the outside of the casing. Controversially, brushless motors coils are fixed either to the outer casing or inside the casing. In most situations, we will be considering only brushless DC motors. “Pancake” brushless motors have a larger diameter and are essentially flatter and often allow for higher torque and lower KV. Smaller tricopter tend to use small brushed motors because of the lower price and simpler two-wire controller. Although brushless motors come in a variety of different sizes and specs, selecting a smaller brushless motor rarely means it will be less expensive. Tricopters usually brushless motors as powerplant. The rotor part of a brushless motor is often a permanent magnet synchronous motor, but can also be a switched reluctance motor or induction motor.

Brushless motors offer several advantages over brushed DC motors, including high torque to weight ratio, more torque per watt (increased efficiency), increased reliability, reduced noise, longer lifetime (no brush and commentators erosion), elimination of ionizing sparks from the brushed motor. Brushless motor commutation can be implemented in software using a microcontroller, microprocessor computer or may alternatively be implemented in analogue hardware or in digital firmware using an CPU .Commutation with electronics instead of brushes allows greater flexibility and capabilities not available with brushed DC motors, including speed limiting, "micro stepped" operation for slow and fine motion control and a holding torque. The maximum power that can be applied to a brushless motor is limited almost exclusively by heat. If the magnet too much heat, the motor may damage. Brushless motors in tricopters is normally indicated by a 4-digit number – AABB. “AA” being the stator width, and “BB” being the stator height.

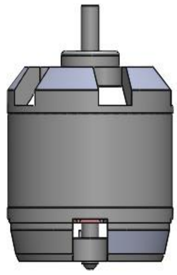

Figure 4. Illustration of brushless DC motor

The KV rating of a motor relates to how fast it will rotate for a given voltage. If the KV rating for a motor is 650rpm/V, then at 11.1V, the motor will be rotating at 11.1V x 650 = 7215rpm. If you operate the motor at a lower voltage (like, 7.4V), the rpm will be 7.4V x 650rpm/V = 4810rpm. It is important to note that using a lower voltage tends to mean that the current draw will be higher (power = current x voltage). KV is the theoretical increase of motor RPM (rotation per minute) when voltage go up by 1 volt without load. Higher KV motors would attempt to spin the propeller faster, but lower KV motors normally generate higher torque. That’s why we recommend to larger propeller are paired with low KV motors, and smaller props with high KV motors. If propulsion used high KV motors with excessively large propellers, the motor will attempt to spin it fast like they would do with smaller propeller and therefore drawing too much current and generating too much heat. Eventually it could burn out the motor or esc due to overheat.

Engine Speed Controller (ESC)

After selecting a motor the next logical step is to select a brushless electronic speed controller (ESC) that matches motor. The motor will have an amp (A) rating in the description of motor. It is good general practice to select an ESC rated for 30 percent or 10A more than the max current draw of your motor. For example, 40 A ESC is recommended for 30A brushless motor.

The engine which is to be used in the tricopter are determined to have a peak power is 338W when the time of starting of take-off. It was determined that the ESCs used with the 4s battery use 22A current. Using the 30A ESC card, which is 30% more than the maximum current, the motor will be able to drive to run easily and safely. The ESC can provide high values of energy such as 30 ampere current continuously and 40 ampere current in short time periods. In order to be able to respond quickly to the command which is given, the speed of renewing the autothrottle must be at least 300Hz. Also as a feature of the ESC, after connecting the battery the engine does not move no matter what level throttle.

An electronic speed control or ESC is an electronic circuit with the purpose to drive an motor, its direction and possibly also to act as a dynamic brake. ESCs are used on electrically powered tricopter, with the variety most often used for brushless motors essentially providing an electronically generated three-phase electric power low voltage source of energy for the motor. An ESC can be a stand-alone unit which plugs into the receiver's throttle control channel.

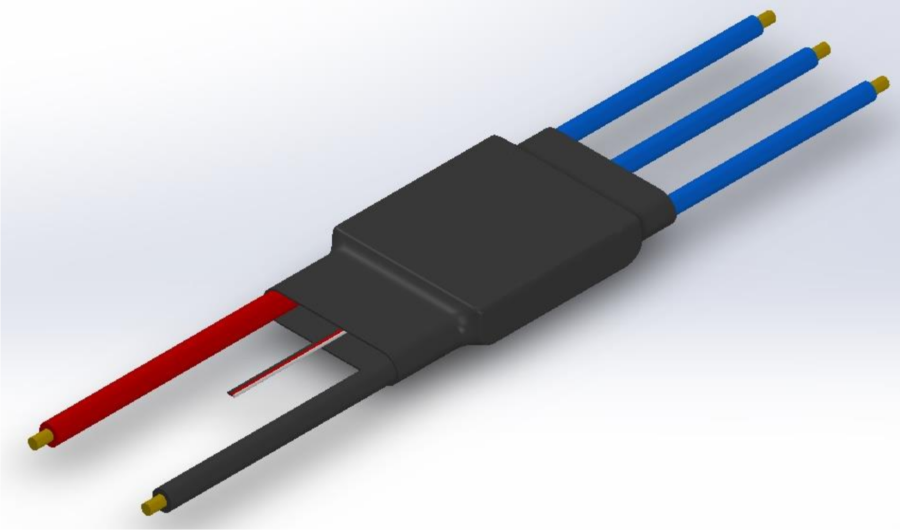

Figure 5. Illustration of brushless ESC

Brushless ESC systems basically create a tri-phase AC power output of limited voltage from an onboard DC power input, to run brushless motors by sending a sequence of AC signals generated from the ESC's circuitry, employing a very low impedance for rotation. An ESC might initially be confusing because it has several wires exiting on two sides.

- Power input: The two thick wires (normally black and red) are to obtain power from the power distribution board / harness which itself receives power directly from the main battery.
- 3 bullet connectors: These pins are what connects to the three pins on the brushless motor. There are some standard sizes in the industry, but if you find the two are mismatched, you will need to replace one set.
- 3-pin R/C servo connector: This connector accepts RC signals, but rather than requiring 5V on the red and black pins, most of the time an internal BEC provides 5V to power the electronics.

If we know the motor’s requirements, deciding which ESC to use is easy. For the ESC to work with our motor, it must be rated for voltage of your battery pack and it must be able to handle the motor’s amp draw. It is always better to have an ESC that is rated slightly higher than the amps need. Variables such as propeller size can push a motor’s amp above the recommend limit and then esc can overheated. Electronic Speed Controllers (ESC) are an essential component of modern tricopters and all multicopters that offer high power, high frequency.

Battery

Lithium Polymer battery (referred to as “Lipo” batteries), is a type of battery which used in electronic flying machines. Lipo batteries have been popular when the radio control industry develop and now the most popular choice for long run times and high power.
Lipo batteries has a various benefits. But each user must decide if the benefits outweigh the drawbacks. For more and more people, they do. In my personal opinion, there is nothing to fear from Lipo batteries, so long as you follow the rules and treat the batteries with the respect they deserve.
Lipo batteries has many advantages than other batteries like nickel-metal hydride (NiMH) or nickel cadmium (NiCd) batteries:

- Lipo batteries are much lighter weight
- Lipo batteries offer much higher capacities
- Lipo batteries offer much higher discharge rates

But lipo batteries has some disadvantages:

- Lipo batteries have a shorter life.
- The sensitive chemistry of the batteries can lead to fire.

Lipo batteries have define by rating system. This system has allows to compare the properties of battery. Moreover this system help users determine which battery pack is suitable. There are three main ratings on a Lipo battery.

Cell account/ Voltage

A lipo cell has a normal voltage is 3.7 V. For the 3 cell battery has 3.7X3=11.1 V and this battery is sometimes called by ‘3S’ battery pack. Some of battery described as ‘2S2P’, this mean there are 4 cell and 2 of them parallel, 2 of them serially connected.

The voltage of a battery is essentially determine how fast your motor is drive. Voltage is directly influences the RPM of the electric motor (brushless motors are rated by kV, which means 'RPM per Volt'). For example we use 950KV brushless motor for tricopter and 3S battery. In the full throttle motor will rotate 11.1X950=10,545 RPM.

Capacity

The capacity of battery is a measure of power which battery can hold. The unit of capacity is milliamp hours (mAh). This unit means how much drain can be put on the battery to discharge it in one hour. The higher number of capacity means the longer using time. But the bigger capacity is the bigger physical size and weight of battery. Lipo batteries should be periodic checked. If tricopter’s average current 9A, at least 3000 mAh battery is required to operate for 15 minutes.

Discharge Rating

Voltage and Capacity had a direct impact on certain aspects of the vehicle. The Discharge Rating is simply a measure of how fast the battery can be discharged safely and without harming the battery. The maximum current that the battery can safely provide in the form of discharge rate X ampere hour.

For example 20 X 2.6= 52 A is the maximum discharge ampere. 52 A is the maximum sustained load you can safely put on the battery. If you exceed the 52A, probably degradation of battery faster than normal pace and maybe it could burst into fire. The example battery has two discharge rate. One of this 20C is continuous rate, other rate 30C is applicable in permanent like 10 second.

Calculation of Thrust

Propeller thrust depend on propeller pitch, diameter, RPM at propeller spinning and forward airspeed of propeller. Here is the thrust equation;

$$F = 1.225\frac{\pi(0.0254*d)^2}{4}*\left[\left(rpm*0.0254*pitch*\frac{1\min}{60}\right)-\left(rpm*0.0254*pitch*\frac{1\min}{60}\right)*v_0\right]*\left(\frac{d}{3.29546*pitch}\right)^{1.5}$$

Staples, G. (2013)

F is thrust by newton
d is propeller diameter by inch
rpm is propeller frequency of rotation by revolutions per minute
pitch ispropeller pitch by inch
V_0 is propeller forward airspeed by m/s

Simplified form of equation is;

$$F = 4.3924*10^{-8}*rpm*\frac{d^{3.5}}{\sqrt{pitch}}\left(4.2333*10^{-4}*rpm*pitch-V_0\right)$$

Staples, G. (2013)

Tricopter is stopped (V0 is "0 m/s") or hang in the air, this equation give us static thrust (F) in unit of newton or else (V0 > 0 m/s) dynamic thrust is calculated by newton and if we want thrust by gram unit, we must just multiply by 1000/9,81.

Note: The equation has an atmospheric density of 1,225 kg/m3, which is the standard day density at sea level.
The figure 6 shows the thrust chart of tricopter which has 10X5 propeller with E-Max GT2815 motor propulsion of one motor.

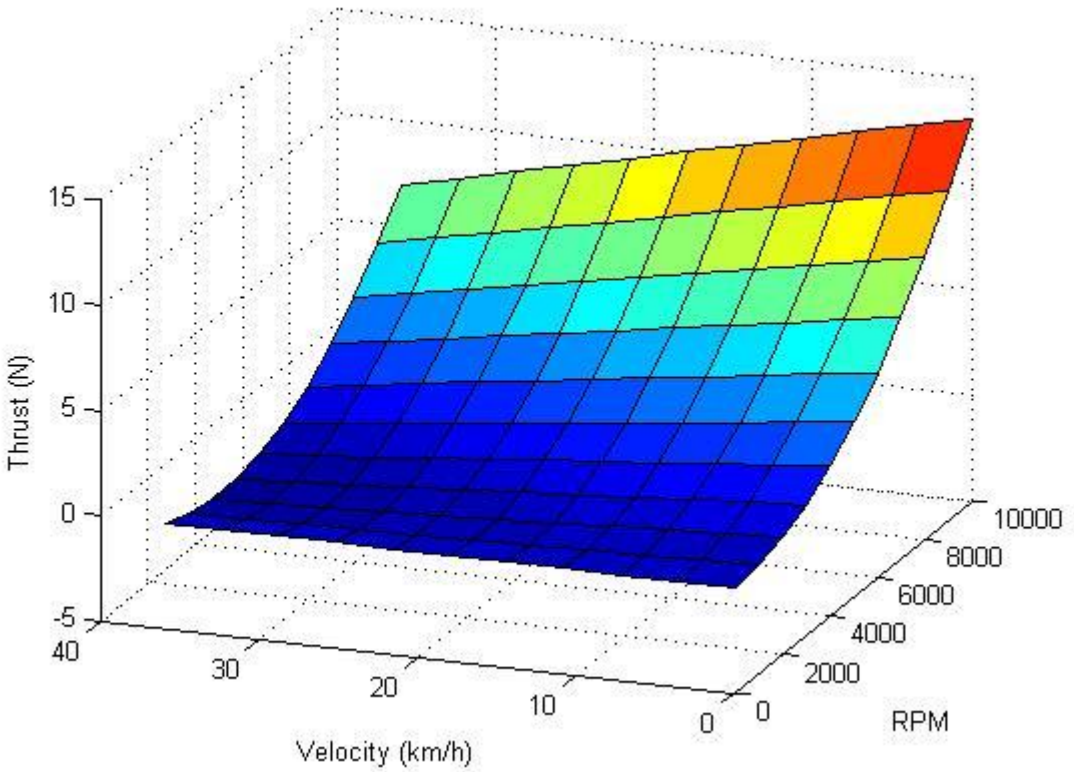

Figure 6. Effect of velocity and RPM on thrust for 10X5 propeller

Changing propeller with 10X6, the effect of thrust graphic shows in figure 7. In this result were obtained same motor (E-Max GT2815).

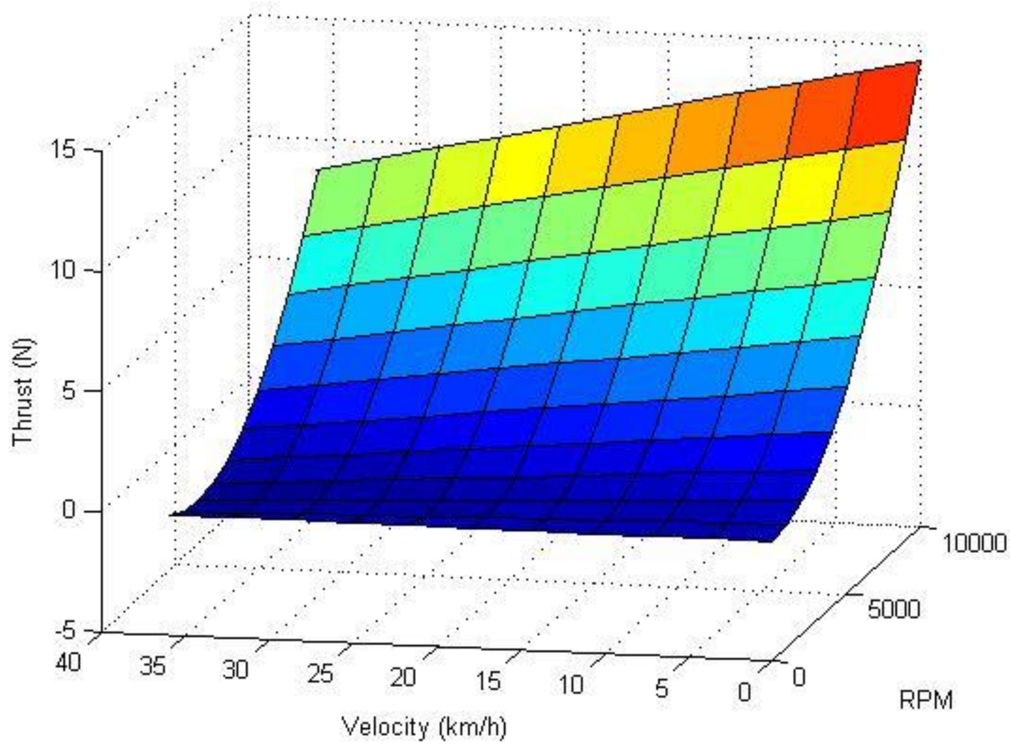

Figure 7. Effect of velocity and RPM on thrust for 10X6 propeller

Another propeller type that the engine manufacturer recommends to use is 11X5.5 propeller. The result of thrust-velocity-RPM graphic is shown in figure 8.

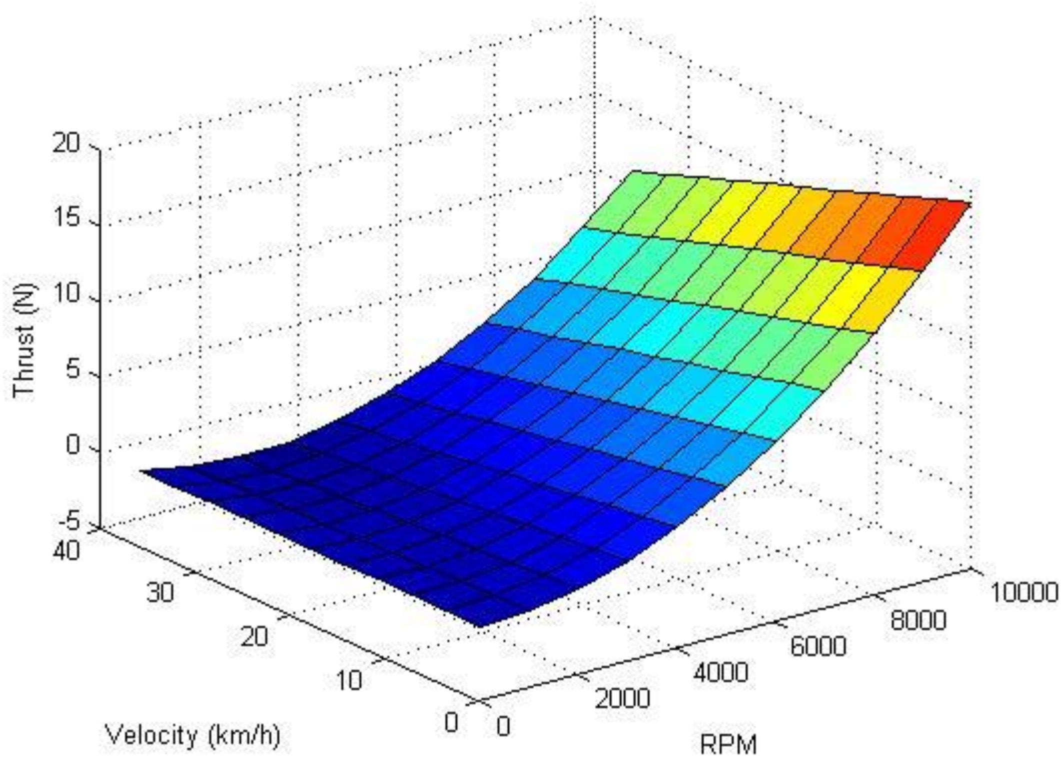

Figure 8. Effect of velocity and RPM on thrust for 11X5.5 propeller

The same diameter and more pitch propeller is 11X6 propellers thrust-velocity-RPM graphic is shown in figure 9. The experiment was carried out with the same motor (E-Max GT2815).

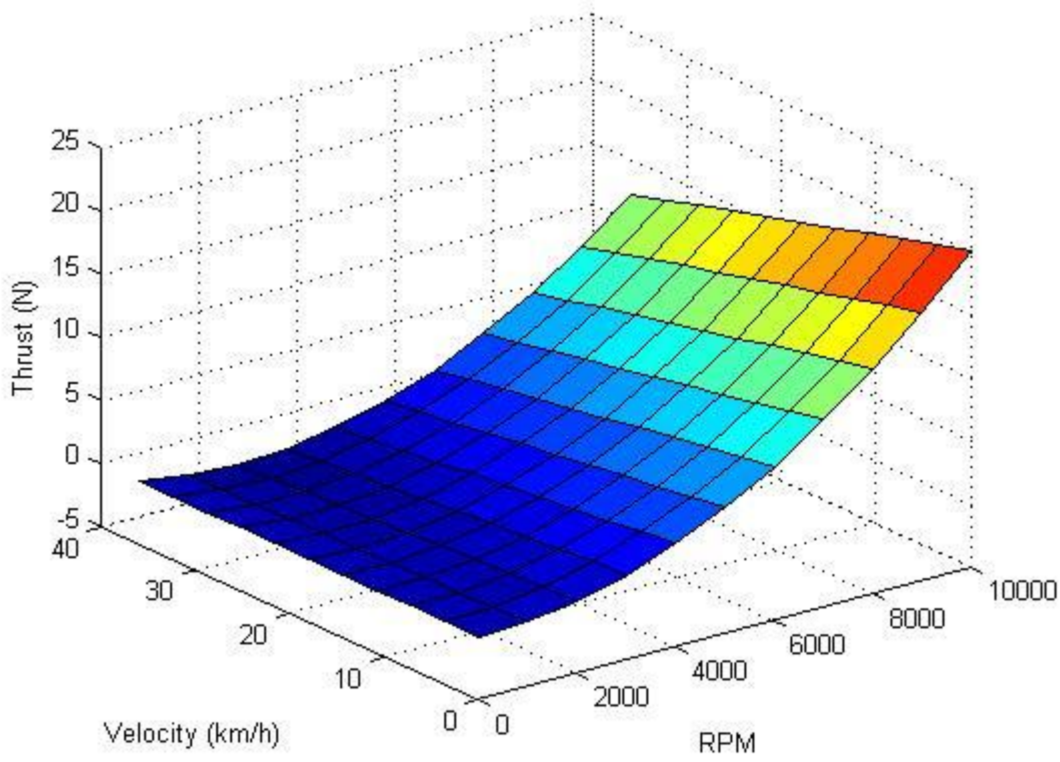

Figure 9. Effect of velocity and rpm on thrust for 11X6 propeller

The same pitch and more diameter propeller is 12X6 propellers thrust-velocity-RPM graphic is shown in figure 10. The experiment was carried out with the same motor (E-Max GT2815).

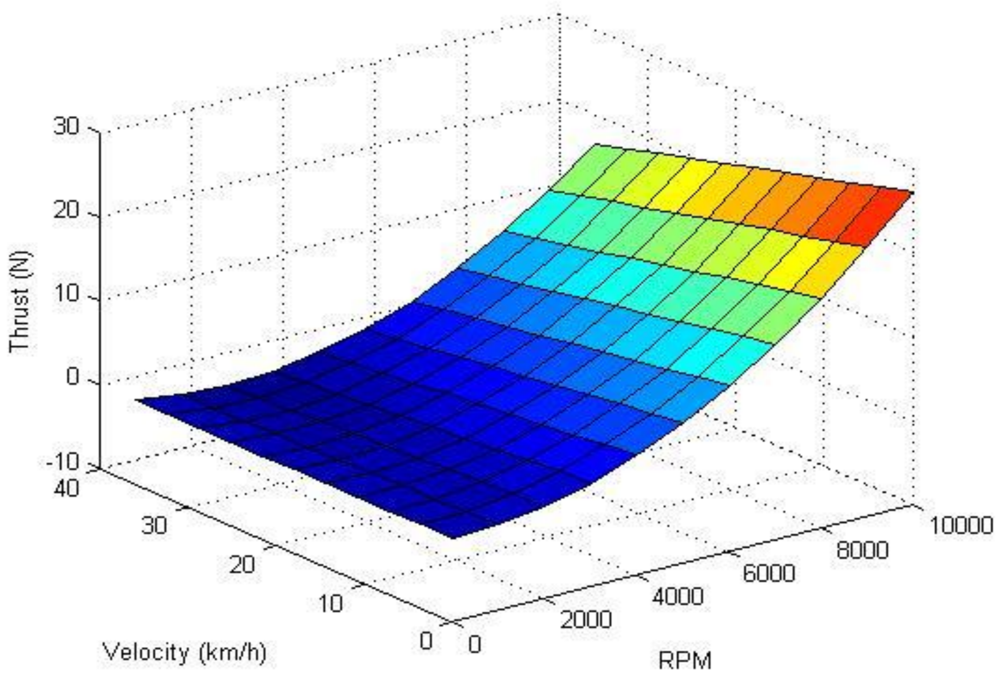

Figure 10. Effect of velocity and rpm on thrust for 12X6 propeller

If we change the propeller diameter from 11” to 10”, airspeed-thrust graph will change like figure 11,

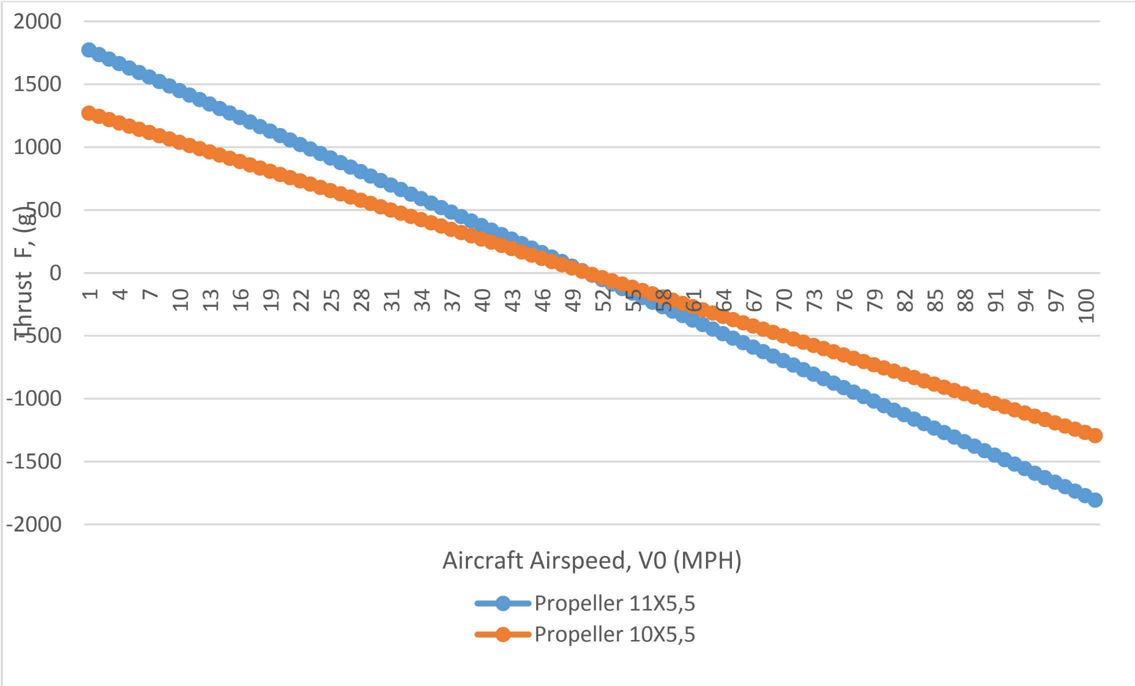

Figure 11. Effect of propeller's diameter on thrust

In figure 7, two different propellers are used the same motor which rpm is 9500. That mean is using longer propeller diameters, produce more thrust power and boundary speed is constant at 50 mph. In both situations, the tricopter won't accelerate more than 50 mph.

If we change the propeller pitch from 5" to 6", airspeed-thrust graph will change like figure 12. Two different propellers are used the same motor which RPM is 9500. The result of this graphic is using the more propeller pitch, produce more thrust power and boundary speed will be change. While the 11X5 propeller with 9500 RPM motor can go maximum speed is 49mph, the 11X6 propeller with same motor can go with a maximum of 57mph.

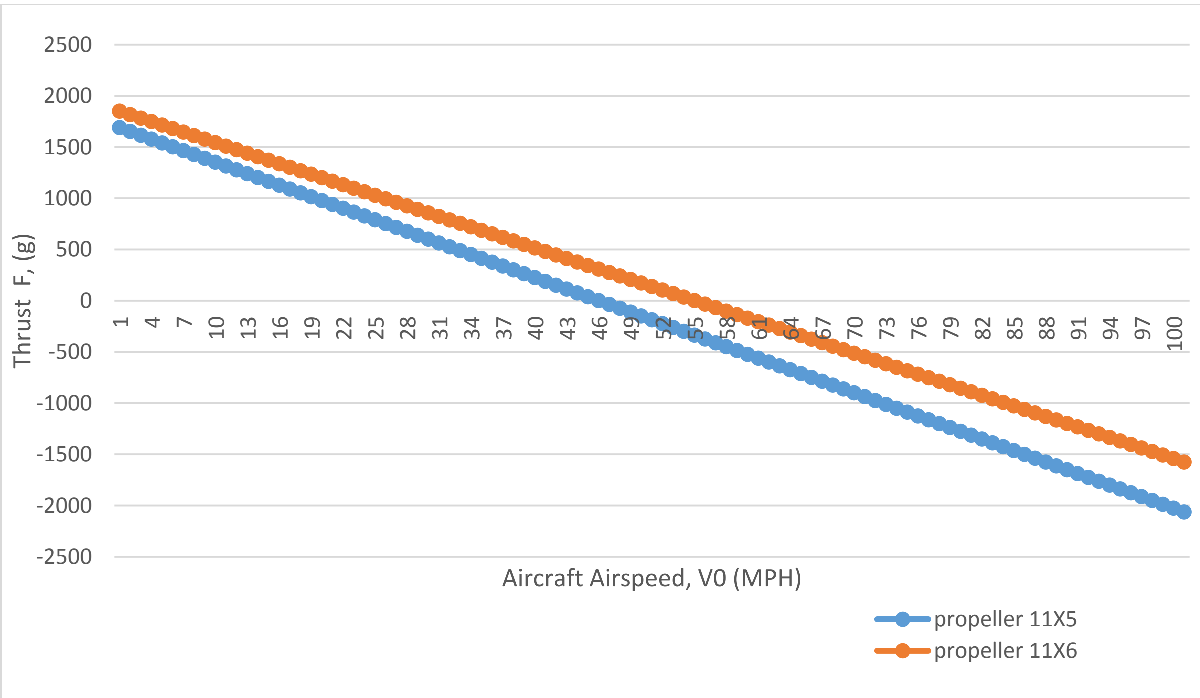

Figure 12. Effect of propeller's pitch on thrust

The result of RPM-Thrust graph in figure 13 is different velocity of tricopter supply different thrust. The experiment was applied by using same motor and propeller (11X5.5 propeller).

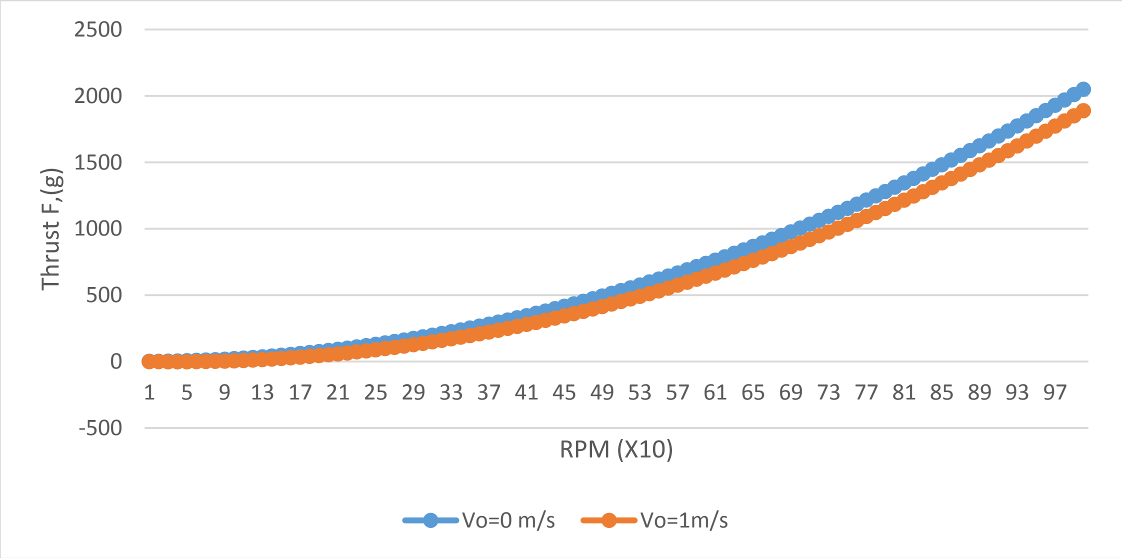

Fig. 13. Effect of propeller's rotation velocity on thrust

If we change motor rpm from 9000 to 3000 airspeed-thrust graph will change like figure 14. Two different motor rpm are used in the same conditions. The result of this figure is the more rpm is used, the more thrust will produce and maximum speed will increase. While the 11X5.5 propeller with 9500 rpm motor can go maximum speed is 43 mph, the 3000 rpm motor with same propeller can go maximum 16 mph.

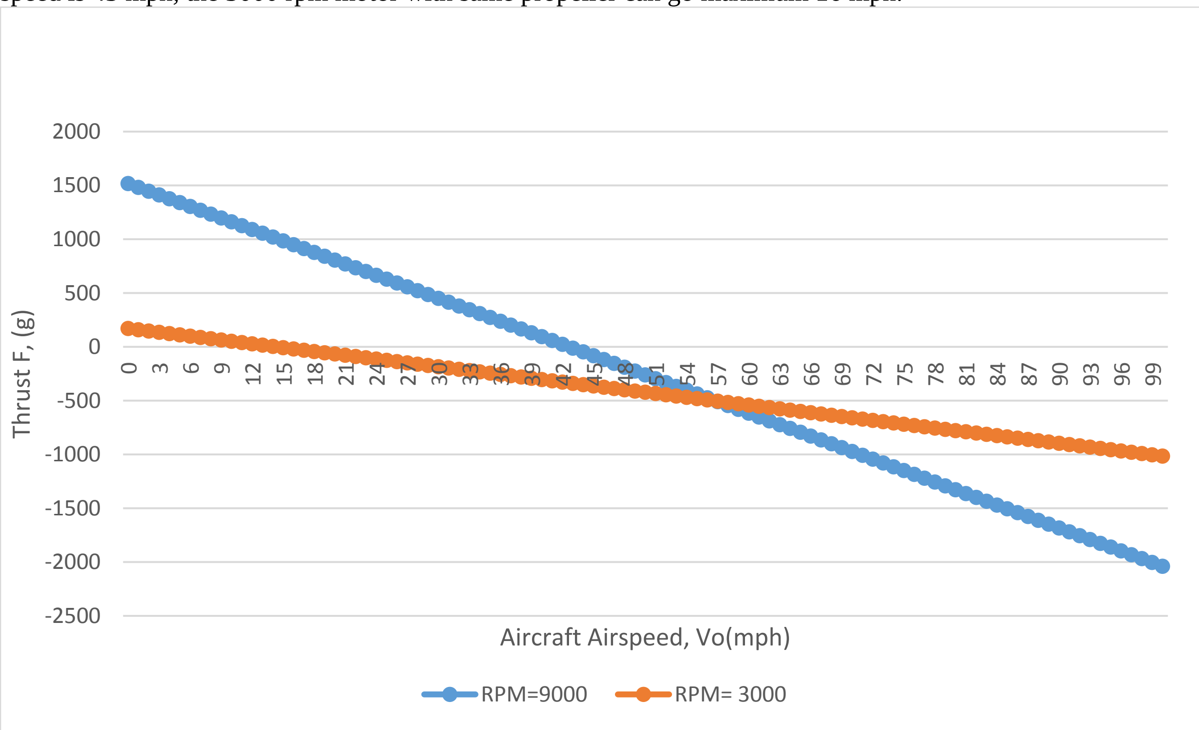

Figure 14. Thrust change with different RPM and velocity

This equations show for one motor and because of the tricopters have three motors, the total thrust value is three times the calculated. That's why we need to base on this value when we choose a propeller, motor and esc combination.

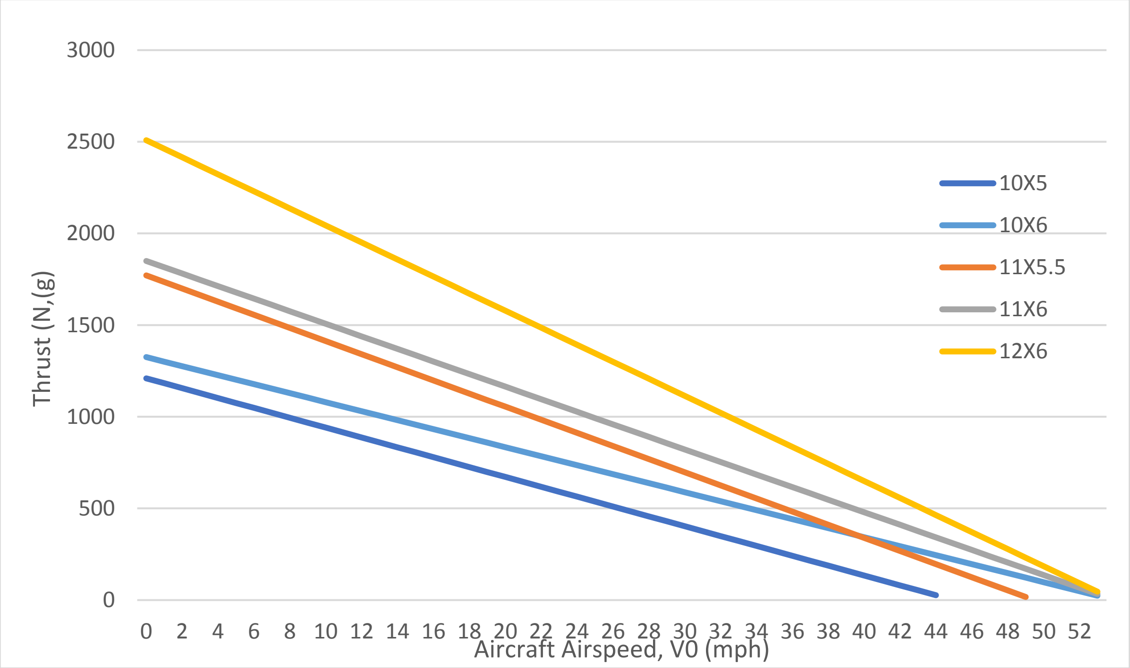

Figure 15. Thrust change with different airspeed (all propeller)

As a result, the graphs of the simulation results with 9000 RPM, including the characteristics of all propellers used in the study, are shown in figure 15. High thrust production requires high power engine. High power motor uses high current so it is necessary to use high current ESC.

Conclusion

In this conference article components of powerplant system for a small unmanned tricopter is designed in order obtain safe and performable autonomous tricopter flight. Result of MATLAB environments are compared by using the effect of propeller, motor velocity and forward airspeed in the article. Changing the pitch and length variables of propeller is proportional to the thrust force. The rotation speed of the motor is exponentially affect the thrust force. Forward speed of propeller of tricopter is inversely to thrust force. All of these thrust results are calculated for vertical axis of tricopter, because the propeller of tricopter is positioned vertically.

Acknowledge

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