Paul-Julius-von REUTER-SCHULE Kassel

A Physical Approach to Drone Flight

A physics project in final year of secondary college

Preface

For an aircraft to stay airborne the force of gravity has to be countered by an at least as big force of thrust. Airplanes accomplish this by their wings which carry them through the air. Their engines only provide for thrust ahead and the airflow along the shaped wings generates the upward thrust.

Drones, i.e. multicopters, have to do without this constructive feature. For this reason they are not suitable for time consuming long distance flights but take advantage in their unique features – extreme maneuverability, vertical take off and landing – in other fields of application.

Questions and answers to drone flight

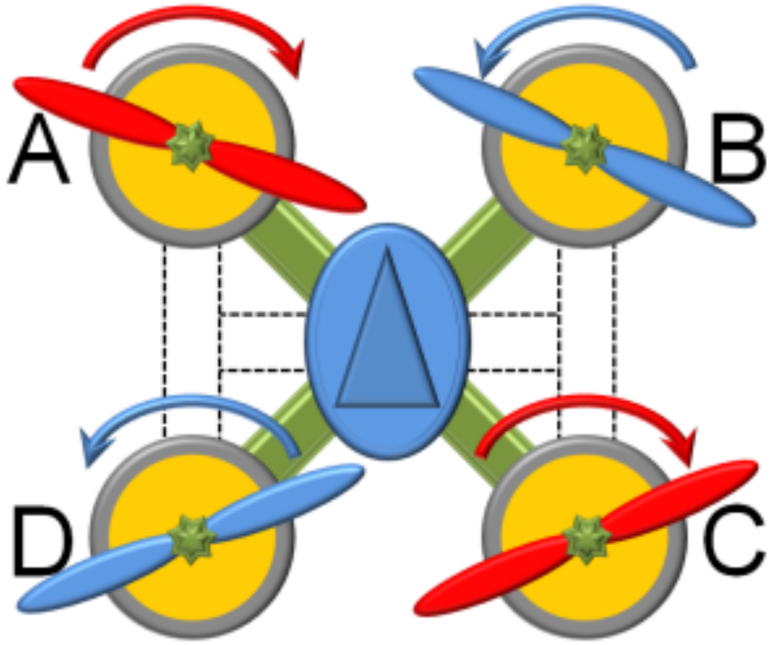
Why are there multicopters with 4, 6 or even 8 motors?

For a multicopter to be volant it needs four powered airscrews. Two of them turn clockwise, two anti-clockwise, hence their torque is compensated and no ineffective tailrotor, like with helicopters, is needed.
A disadvantage of four-engine multicopters is the absence of redundancy. If one engine fails the aircraft crashes down. To compensate for this danger six or eight motors are used. If there is an engine failure with a hexacopter (six motors) there is still a chance of an emergency landing. However, if the flight situation or the load is critical, the craft will crash nevertheless. This is why some manufacturers rely on octocopters (eight motors) with their high performance products because this configuration provides for a maximum redundancy.

Which physical properties affect take off, flight and landing?

For the lift off, as mentioned before, gravity has to be overcome by the force of thrust. This needs, depending on the weight, a different number of differently powerful motors with rotors of different size. Engine power and speed, size of rotors and battery power finally decide on how long the craft can stay in the air, the speed of lift and the load it can carry.
To enable an exactly vertical lift all rotors have to turn at the same speed, in addition, they have to turn oppositely for their torque to be compensated. If they don't, the craft will turn around its vertical pivot.
These motions are measured and controlled by an accelerometer (measuring acceleration) and a gyrometer (measuring turn or twist). These devices, by the way, are found in every smartphone.
Steering of the craft is done by a change of turning speed of the rotors. Opposing rotors have to turn in the same direction, i.e. A and C turn in a different direction than B and C.
To lift upward all rotors have to turn faster because then the generated upward thrust is bigger than the force of gravity trying to force the craft downward. To move the craft downward the opposing factors apply.
To turn right rotors B and D have to turn faster than A and C, to turn left A and C have to turn faster than B and D. In addition, for a turn to the right, A and D should turn faster to

increase thrust on the left side, the opposite applies for a turn to the left, B and D turn faster than A and C



.

To move ahead D and C have to turn faster than A and B to increase thrust of "the back". If A and B turn faster than C and D, the craft will move backward.

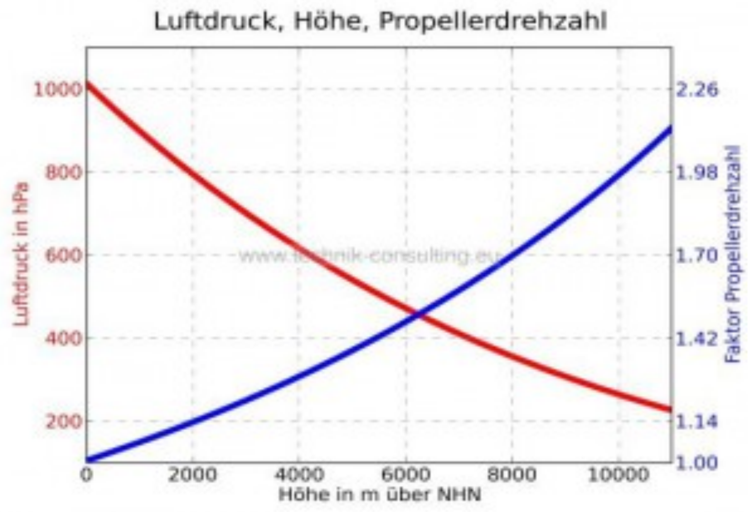
How does thrust change with increasing hight?

Since air pressure and air density decrease with hight, the turning speed of the rotors have to increase to compensate for this effect. This means that the higher the craft moves the bigger the rotor speed, e.g. if the screws rotate at 8000 rpm at sea level they have to rotate at a speed of 9120 rpm at a height of 2000 m in order to generate the same thrust.

Here's the calculation with data taken from diagram below:

8000 U/min x 1,14 (Faktor) = 9120 U/min

The rotor speed, by the way, cannot be increased at will without running the risk of damaging the screws. The motors likewise have a maximum drive. The following diagram shows the correlation of rotor speed and air pressure.



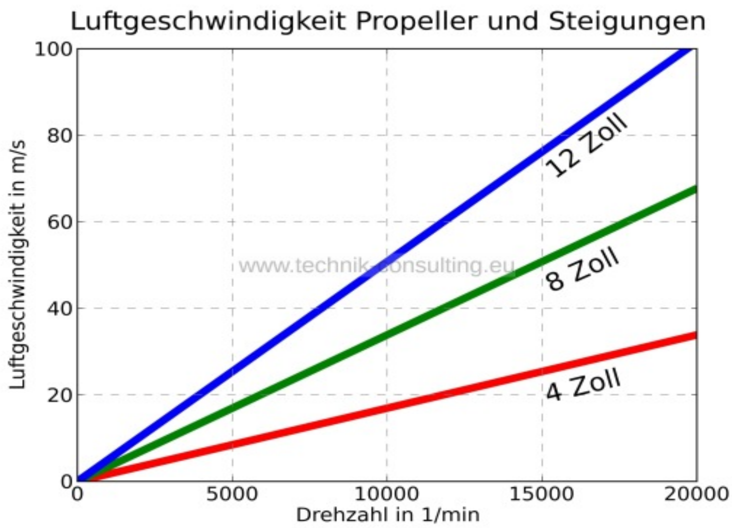
Now, how do we calculate the thrust generated by the rotors? The following formula applies:

$$F = \frac{m_{\text{Luft}} \cdot (v_{\text{Luft,out}} - v_{\text{Luft,in}})}{\Delta t}$$

The rotor thrusts downwards in constant time intervals Δt packages of air of the mass m_{air} at a speed of $v_{air,out}$. When the rotor moves through the air at a speed of $v_{air,in}$ it has to “capture“ these air packages beforehand. The bigger the difference of the masses of these air packages and their velocities, the bigger the generated thrust.

What is the correlation between the speed of the air stream $v_{air\ out}$ and the lift speed of the craft?

The maximum lift speed is limited by the rotor diameter, blade pitch angle and rotation speed. Depending on size and rotation speed of the rotors different speeds of air stream result which directly influence lift speed. The diagram below visualizes these correlations.



However, we need to consider that the real air speed is approximately 10% less than indicated owing to losses of streaming. The air stream generated by the rotor has to be significantly faster than the lift speed. E.g. if a lift speed of 70 km/h, i.e. 19 m/s, is meant to be achieved, a rotor diameter of at least 8 inches at a rotation speed of at least 8000 rpm is needed.

Which records (speed, acceleration) have been achieved so far?

Drones, i.e. multicopters, have become pretty powerful today. There are even contests for top speed and acceleration. The current world record is held by a research drone of a total weight of 0.9 kg. Its maximum engine power was 2.300 Watts, power to weight ratio was 0.393 kg/kW. It accelerated to 100 km/h in 1.3 seconds, reached a lift speed of 189 km/h, i.e. 52.2 m/s and reached a hight of 100 m in 3.871 s. In comparison, a fast passenger aircraft reaches a lift rate of 25 m/s.

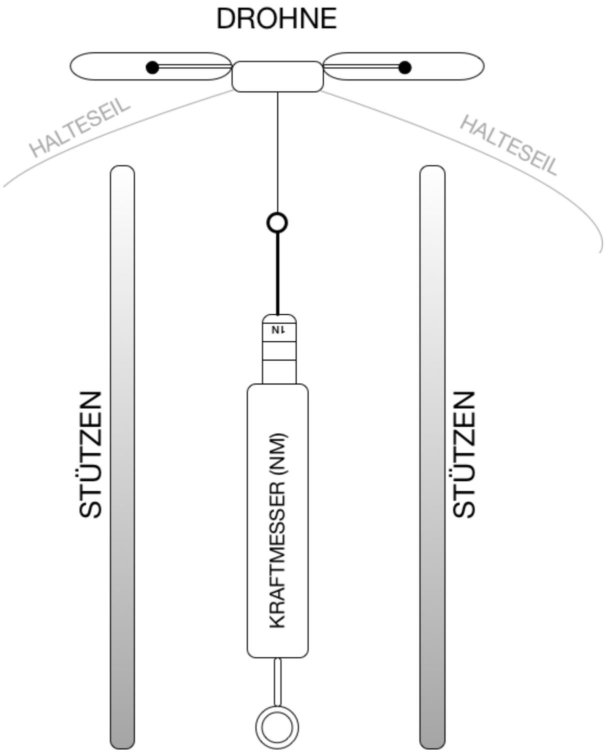
Let us now calculate the acceleration of this record keeping multicopter.

vertical **(data taken from the paragraph above)**	**horizontal** **(data taken from the paragraph above)**
<u>given:</u> **Δv = 100km/h = 27,78m/s** **Δt = 1,3s** **<u>wanted:</u>** **a = ?? m/s^2** **$a = \Delta v / \Delta t$** **a = 27,78m/s / 1,3s** **a = <u>21,37m/s^2</u>**	**<u>given:</u>** **s = 100m** **Δt = 3,871s** **<u>wanted:</u>** **a = ?? m/s^2** **$s = a/2 * t^2$** **$a = 2 * s / t^2$** **a = 2 * 100m / $(3,871s)^2$** **a = 200m / 14,984641s^2** **a = <u>13,35m/s^2</u>**

So the vertical acceleration is an impressive 21.37 m/s^2, horizontal acceleration at 13.35 m/s^2 is still far beyond the fastest sportscar. In comparison, the acceleration of the Saturn V – rocket was 40 m/s^2 at burnout of the first engine. Gravity accelerates any object, not considering air resistence, at 9.81 m/s^2,i.e. reaching a speed of 100 km/h in 2.83 seconds.

Determining the thrust of a homemade drone.

The following setup suggests a way of measuring thrust:



The drone rests on two poles, the stabilizing strings need to be slightly longer than the expected extension of the newtonmeter. While launching the aircraft the upward force can be directly read.

Newton's law of acceleration yields the acceleration **a** through a simple calculation:

$$F = m * a$$
$$(1N = 1kg * m/s^2)$$

Thrust – weight ratio

The acquired measurements and calculations enable us to assess the flight properties of the aircraft since the thrust – weight ratio is the decisive factor.

Ratio 2:1 (thrust to weight) – The copter can basically be flown but is very sensitive to gusts or steering impulses. Furthermore, it can hardly be stabilized again after a sheer descent or dive. Thus it's not suitable for more dynamic operations.

Ratio 3:1 – This copter can be flown very well, it is not too sensitive to gusts or rapid steering impulses and descents can be stabilized easily.

Ratio 4:1 – With this ratio copters enter the field of aerobatics and are used in contests. Flight properties are excellent.

© E. Palmowski 2017, translation into English by A. Gutenberg 2018