Things One Can Learn by Putting a Quadcopter in a Vacuum Chamber

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Quadcopters (also known as "drones") do not fly in vacuum. This is obvious enough that experimenting on one in a vacuum chamber would seem rather uninteresting, but there is one question that may be usefully addressed by such an experiment: the mechanism for yaw control. Quadcopters control yaw (rotation about the vertical axis) by differential rotor speed, and the question of whether those changes in rotor speed create yaw torque via conservation of angular momentum or via atmospheric drag can be addressed by "flying" a quadcopter in a vacuum where there is effectively zero atmospheric drag.

Introduction

For clarity in the following discussion, we will use the right-hand rule to indicate the direction of rotation and of angular momentum. Curl the fingers of the right hand to follow the rotation of the propeller, and the extended right thumb will point in the direction of the rotation. For example, a propeller rotating clockwise when viewed from above would have *down* rotation, and since $L = I\omega$, the angular momentum L would also be in the *down* direction.

Multi-rotor drones with an even number of propellers (quads, hexes, octos) are configured so that half of the propellers rotate clockwise (*up*) and half rotate counterclockwise (*down*).[1] The clockwise and counterclockwise props are distributed symmetrically around the center of the aircraft so that one can increase the angular speed ω of one set while simultaneously decreasing the speed of the other without affecting lift, roll, or pitch (see Fig. 1).

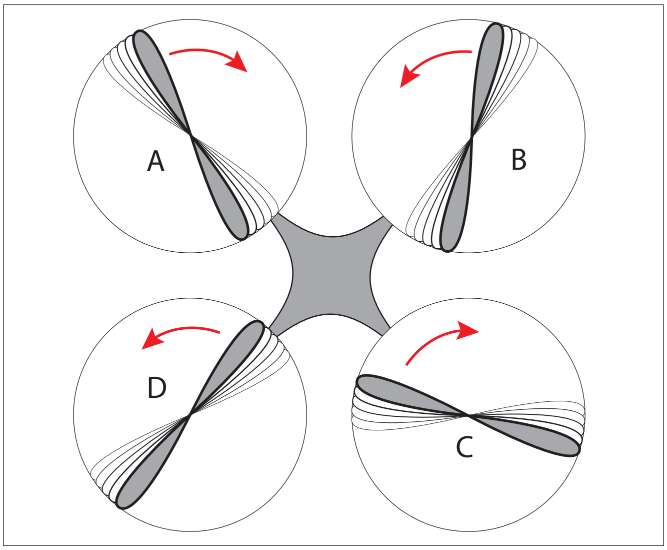

Fig. 1. Typical quadcopter design. Propellers A and C rotate clockwise (*down* using the right-hand rule); B and D rotate counterclockwise (*up*).

Conservation of angular momentum is one mechanism for yaw control.[2] If a quadcopter is hovering, it has a total angular momentum L of zero. The body of the quad is not rotating, so $L_b = 0$. The angular momenta of the *down* props (A and C in Fig. 1) and *up* props (B and D in the same figure) cancel, since they have the same rotational inertia and opposite angular velocities: $\Sigma L_p = 0$. Increasing the angular velocity of the *up* props and decreasing the angular velocity of the *down* props causes a net *up* angular momentum of the props: $\Sigma L_p > 0$. The total angular momentum $L_b + \Sigma L_p$ must remain zero, so the resulting body angular momentum $L_b = -\Sigma L_p$ and the quadcopter yaws *down.* (To the right, as viewed by any bugs in the quadcopter cockpit.)

Atmospheric drag is the other mechanism. The assumption made in considering conservation of angular momentum is that the external torque is zero; but that's not really the case. Drag on the *up* prop causes a *down* torque, and vice versa. Increasing the angular velocity of the *up* props increases the *down* drag torque. Simultaneously decreasing the angular velocity of the *down* props decreases the *up* drag torque. The net result is an increased torque in the *down* direction, which results in a turn to the right. On the one hand, air has a low density and one would not expect the drag torque to be large, but on the other hand the magnitude of the drag torque goes as ω^2,[3] so changes in propeller speed will have an outsized effect.

Both of these mechanisms may contribute to quadcopter yaw. Our goal for this investigation was to determine how much each mechanism contributed to the overall effect. By placing the quadcopter in a vacuum chamber, we could remove the atmospheric drag mechanism and observe how much the yaw rate decreased as a result.

Experimental details

We chose the Ares RC XView FPV RTF Mini Electric Quadcopter Drone as our test device, because it was the biggest and cheapest quadcopter we could find that still fit in our vacuum chamber. Since quadcopters don't fly in vacuum, and since we wanted to make quantitative measurements of yaw rate, we 3D printed a lightweight adaptor platform that allowed us to mount the quadcopter on a PASCO CI-6538 Rotary Motion Sensor.[4] The rotary motion sensor was mounted in the chamber so that the quadcopter was supported and constrained to rotate only around the vertical axis. The sensor's leads connected to an electrical feedthrough so that it could be powered (and read) from outside the chamber.

We wanted to measure the angular velocities of the propellers also. To do this we 3D printed a "saddle" that fit on the quadcopter and held miniature photogates[5] aligned with

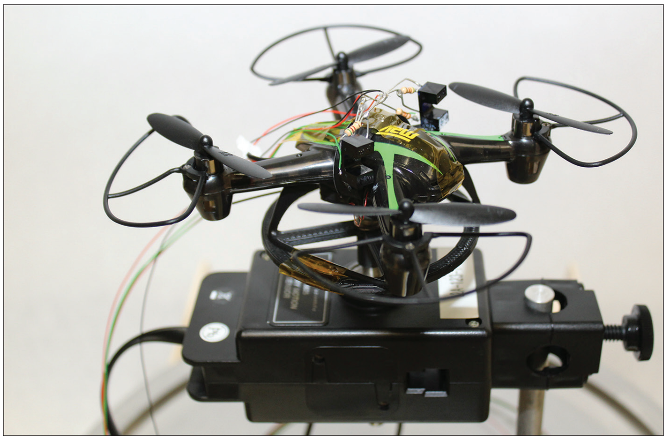

Fig. 2. Quadcopter, with supply wires and propeller-sensing photogates, ready to mount in the vacuum chamber.

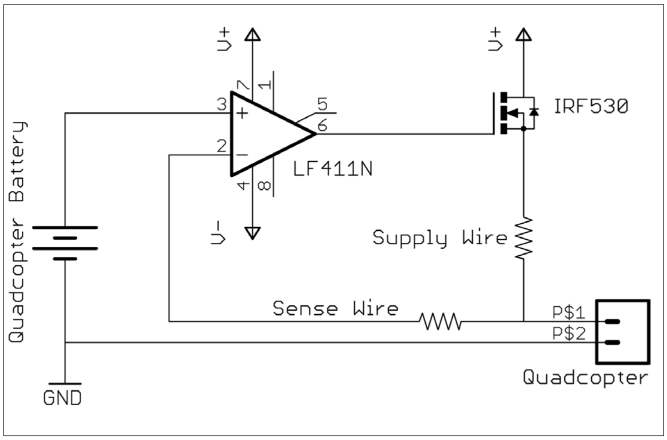

Fig. 3. Voltage regulation circuit to provide constant "battery" voltage to the quadcopter. The op-amp adjusts the gate voltage at the power MOSFET so that the voltage at the quadcopter is equal to the voltage across the quadcopter battery. This external battery is used only as a reference voltage; the quadcopter power is supplied by external power supply *V*+ through the MOSFET.

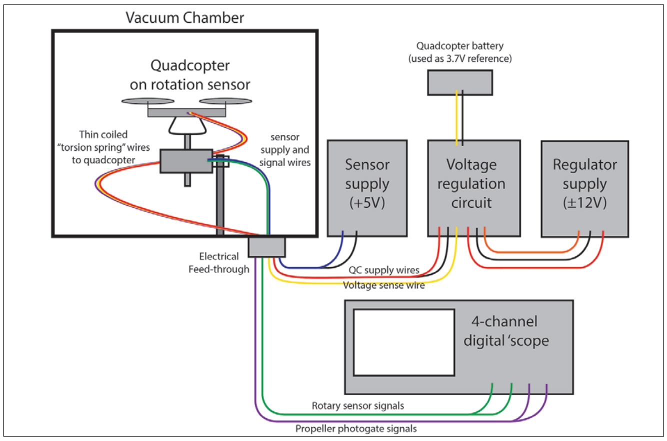

Fig. 4. Schematic representation of the experiment.

two counter-rotating propellers. The photogates had phototransistor sensors, so we connected the sensors in common-emitter configuration with 10 kΩ pull-up resistors. Every time a blade of the propeller went through the photogate, it produced a voltage pulse; by timing the intervals between these pulses we could measure the propeller angular speed ω. Figure 2 shows the quadcopter, with photogates, mounted on the sensor and ready to insert into the vacuum chamber.

It should be noted that 3D-printed objects are not, in general, vacuum compatible. They have significant outgassing, as did the PASCO sensor and the quadcopter itself. For our experiment, rough vacuum was sufficient, although the amount of outgassing from all of these plastic parts would probably cause issues if we tried to get below a few millitorr.

The quadcopter flight battery was a 3.7-V lithium polymer battery, and the risk of a "sudden uncontrolled exothermic battery expansion" that left the chamber coated with toxic residue was judged unacceptable. Instead, we chose to power the quadcopter via an external power supply. Delivering the external power was something of a challenge because we wanted the quadcopter to be able to rotate as freely as possible. Long thin wires were used to minimize external torque, but the resistance of those wires was significant. The voltage drop across the supply wire would lower the voltage at the quadcopter, which would then shut down because it sensed a "low battery." In addition, the power draw of the quadcopter varied from 40 mA at idle up to nearly 3 A at full throttle, so the supply-wire voltage drop could vary by a factor of 75 during an experimental run! To combat this issue, we built an op-amp circuit that automatically adjusted the external voltage so that the voltage at the quadcopter (measured by the "Sense" wire) remained at the required 3.7 V (see Fig. 3).

We now had five wires directly attached to the quadcopter: V_{supply}, V_{sense}, two photogate signals, and ground. To minimize the torque from these wires and allow significant rotation, we wound the wires in a wide free-standing spiral from the vacuum base plate to the quadcopter. The wires then formed a weak torsion spring, which provided both a zero point for the quadcopter angular displacement and a means of qualitatively estimating torque from that displacement.

The final complication was that the quadcopter normally cooled itself by convection. (There are four fans on it, after all.) But in vacuum, convective cooling is sharply limited. We never determined whether it was a thermal cut-off circuit in the quadcopter electronics, or ohmic heating of the supply wire causing resistance beyond what our regulator circuit could correct for; but we were unable to operate the quadcopter in vacuum for more than about 10 seconds at a time. In the end we just ran it for short bursts, interspersed with intervals of rest while we saved data from the four-channel oscilloscope with which we observed the propeller photogate and PASCO Rotary Motion Sensor data.

Results

Figure 5 shows results of a typical 2-s data run, at standard atmospheric pressure. The procedure was to bring the quadcopter up to mid-throttle, start an oscilloscope sweep, give the controller full right rudder, and then cut the throttle for a cool-down interval as soon as the sweep finished. We

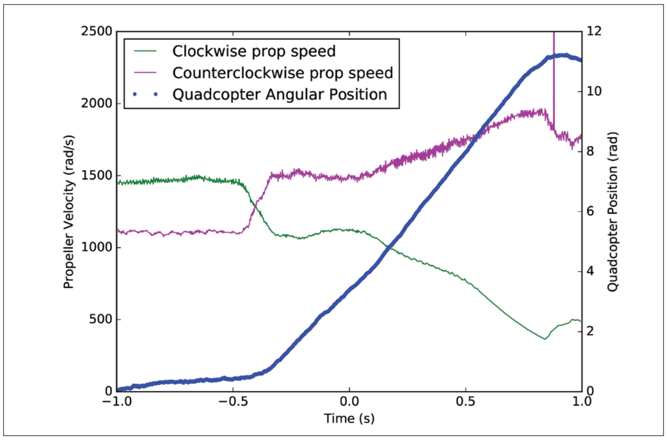

Fig. 5. Turning right, at atmosphere pressure.

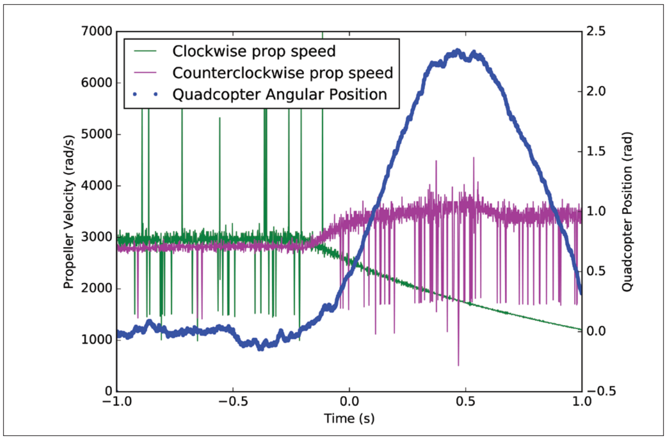

Fig. 6. Turning right, in vacuum.

then saved the raw data from the 'scope and used a Python program to extract the angular velocities of the props and the angular position of the quadcopter from the 'scope data.

One can see in Fig. 5 that both props (light green and maroon lines) change speeds to initiate the yaw. The angular position of the quadcopter (heavier blue line) increases almost linearly well past 10 rad. Note that the quadcopter continues to adjust the speed of the props throughout the experiment as it attempts to maintain the yaw rate against the increasing torque of the wiring.

Compare this with Fig. 6, which shows the same experiment at rough (millitorr) vacuum. The noise in the propeller angular velocity measurements has gone up significantly, possibly due to the higher angular velocity, which is double that of the props at atmospheric pressure. Setting that increase in noise aside, one may also note that the speed of the faster prop stays roughly constant after the initial increase in speed, even when the quadcopter is rotating the opposite direction from the desired yaw. The slower prop follows an exponential decay curve, suggesting that power has been cut completely and that prop is merely slowing down under the effect of friction in the bearings. Finally, the angular displacement of the quadcopter is much lower, and even changes direction after reaching a maximum of just over 2 rad. Taking these three points together, one may infer that the quadcopter is unable to regulate its yaw rate in vacuum. The initial changes in angular velocity of the props give an angular impulse to the quadcopter, which then coasts to the maximum angle. After the quadcopter reaches that maximum angular displacement, the torsion spring returns the quadcopter to center despite one prop spinning at maximum velocity and the other coasting to a stop.

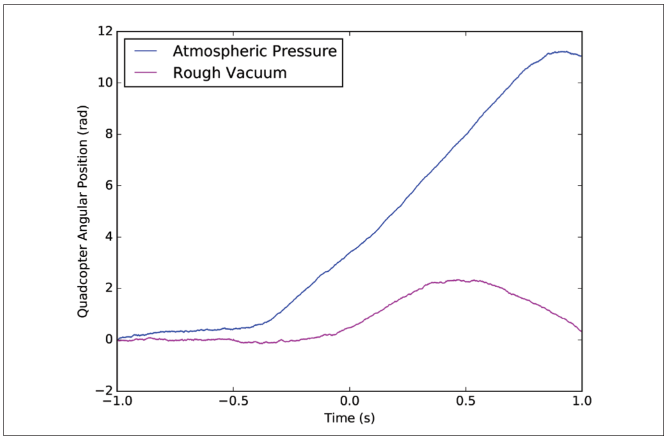

Fig. 7. Direct comparison of the angular displacements from Figs. 5 and 6.

Conclusions

Figure 7 directly compares the two angular displacement graphs. From the relative displacements of the two against the same torsion spring, one may conclude that the combination of both yaw mechanisms is five times more effective than angular momentum conservation alone. However, one must also note that in vacuum the propeller angular velocity was approximately twice what it was at atmospheric pressure. Since angular momentum is linear with ω, the effect observed in Fig. 6 was roughly twice what would have been observed had the props been moving the same initial speed as in Fig. 5. Combining these observations, we estimate that angular momentum conservation accounts for approximately 10–15% of the yaw rate of this quadcopter.

The exact amount of the contribution is of limited interest, as (1) it depends on construction details of the particular quadcopter model, and (2) it's not a burning question that keeps physicists up at night. But the fact that conservation of angular momentum contributes a *minority* of the yaw control should be of interest to physics teachers. One of the authors of this paper has been incorrectly using quadcopters as an example of conservation of angular momentum in his introductory physics course for several years now, and it's good to be set straight.

Acknowledgments

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References

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