Name: _____ Date: _____

The Loop That Holds a Drone Up

Reading level 14 · 1753 words

On December 18, 1922, a four-rotor helicopter built for the US Army made its first public flight, and by the end of 1923 it had flown about a hundred times. It showed that four rotors could lift a machine and a pilot. It also showed how hard that was to fly: in hover, the pilot had so much to do that trying to move sideways was too much. A century later, a builder stands in a parking lot with a laptop and a small quadcopter that will not hold still. The rotors are not the new part. The hard part was the balancing. A small, light machine has so little inertia that a computer can do the work, and between 2005 and 2010 cheap flight controllers, sensors, GPS and cameras arrived together.

Lift is a reaction. A rotor throws air down, and the machine is pushed up. NASA explains that a solid object turns a flow of air, and the lift is generated in the opposite direction, as Newton's third law requires. With no air there is no lift, and with no motion between the object and the air there is no lift. NASA's equation puts numbers on this: lift equals a lift coefficient, times the air density, times half the velocity squared, times the area. Squared is the key word. Double the speed of a blade through the air and, all else equal, the lift quadruples. That is why a quadcopter changes its lift by changing the speed of each rotor.

Holding that lift costs energy, and the builder wants to know why her pack drains so fast while the machine just sits there in the air. The cost can be estimated. Momentum theory treats a rotor as an ideal disc with no friction, and for a hover it gives the least power needed: the square root of thrust cubed, divided by twice the air density times the disc area. Suppose a one-kilogram machine, which weighs about 9.8 newtons, has four rotors 25 centimeters across, a disc area of 0.196 square meters in all. NASA's atmosphere equations give sea-level air a density near 1.225 kilograms per cubic meter. The ideal hover then needs about 44 watts. The formula holds a lesson: a wider disc needs less power to hold up the same weight. The model leaves out friction, so a real machine needs more. The builder types the numbers into a spreadsheet and is surprised how small the answer is.

Now the battery, which is where the surprise ends. Lithium-ion cells store roughly 100 to 250 watt-hours per kilogram, so 100 grams of cells holds 10 to 25 watt-hours. At 44 watts, a perfect hover would last 14 to 34 minutes, and a real machine needs more power than the ideal, so these are upper limits. One maker lists 34 minutes for a camera drone under 249 grams, in a windless wind-tunnel test, and a popular quadcopter of 2013 was listed at about 15. Those are different machines, so only the scale compares. Flights of several hours have been certified, but only on heavy machines that carry a very large battery. The builder writes the range on a whiteboard beside her quadcopter and draws a box around it.

The same cells can overheat. The FAA says lithium-ion batteries can go into thermal runaway without warning if damaged, wet or overcharged, and a fire department advises charging only with the charger that came with the device. Weight bites twice: a bigger battery stores more energy, but every gram of it is a gram the rotors must also lift. The builder reads the label on her own pack and does the same sum, and her charger is the one that came with it. She writes both results on the same whiteboard. Neither number is exact, and both are only a starting guess, but they show how big the problem is.

Holding the machine up is the rotors' job, and the builder knows it. Keeping it where it should be is the flight controller's job, and its structure is a cascade of loops. In PX4, an open-source flight stack, a simple P controller turns a position error into a velocity to aim for. A PID controller turns that velocity into an acceleration, which becomes targets for thrust and tilt. The innermost loop, the rate controller, runs three independent PID controllers for roll, pitch and yaw. Think of the loops as managers: the outer one decides where the machine should go, and the inner ones decide how hard each blade must push right now. Each PID controller compares a target with a measurement and answers the error three ways: in proportion to the present error, to the sum of past errors, and to the trend.

Speed makes the cascade work. ArduPilot, another open-source system, runs its rate controllers at its main loop speed. At 400 hertz, the top of its normal range, a correction can happen every 2.5 milliseconds. Newer versions can run the rate loops near the gyro sampling rate, up to 4 kilohertz. At 400 hertz, a gust lasting a tenth of a second meets 40 corrections. Tuning is a balance: the proportional gain gives a quick response and is set as high as possible without oscillation. The derivative gain damps the motion, but if it is too high the motors turn twitchy, because it amplifies noise. The guides warn that large gains may cause dangerous oscillations. In the parking lot, the builder lowers the gains one small step at a time, flies again, and watches the twitch fade. Those are small steps taken very often, and the machine never tires of them.

A controller can only act on what it believes, and what it measures is noisy, and without good measurements even the best controller would be steering from a blurred map. The inertial measurement unit pairs accelerometers, which report specific force, with gyroscopes, which report angular rate. Cheap MEMS gyroscopes are small enough for phones. In PX4 the gyro signal passes through calibration, bias removal and two filters before the rate controller sees it. Above that sits a Kalman filter, an algorithm that combines a series of noisy measurements into estimates better than any one of them, and PX4's navigation filter is an extended version of it. A barometer adds altitude, since pressure falls as height rises, and the IMU can carry a position estimate through a gap in GPS, such as a tunnel.

GPS gives the outer loop its position, and it has limits. GPS.gov says a phone is typically accurate to within about 16 feet under open sky, and worse near buildings, bridges and trees, where signals are blocked or bounce off walls. Some drones also use cameras and an

infrared sensor to look for obstacles. Return-to-home inherits these limits. In ArduPilot the copter first climbs to a set height, about 50 feet by default, then flies a straight line back, even across a fenced-off zone unless path planning is switched on, and it needs a reliable position from GPS and a compass. A phone's sixteen feet would be a lot of error near a wall or a tree.

The same position data has a legal use. Drones that must be registered, which means 250 grams (0.55 pounds) or more or any drone flown for work, must carry Remote ID, and since September 16, 2023, they may not fly in United States airspace without meeting that rule. There are three ways: a drone with broadcast built in, a drone with a broadcast module, or a flight inside an FAA-recognized identification area. A module must be able to send seven items: the aircraft's serial number, position, altitude and velocity, the take-off point's position and altitude, and a UTC time mark. None of the seven describes what the camera sees. With a module, the pilot must keep the drone in sight and land as soon as practicable if the broadcast stops.

The FAA says Remote ID lets it, police and other agencies locate the control station when a drone is flying unsafely or where it is not allowed. Where drones are allowed depends on airspace classes. The FAA's manual describes Class B as generally the surface to 10,000 feet above sea level around the busiest airports, and Class D as generally the surface to 2,500 feet above the airport around those with a control tower. The pattern is plain: the busier the airport, the taller the zone around it. A recreational flyer needs prior FAA authorization to fly in either. LAANC checks a request against facility maps, special use airspace and temporary flight restrictions, and it can answer in near real time. In uncontrolled Class G airspace the limit is 400 feet, with the drone in sight. These are the rules in fall 2026; the FAA is still finishing a separate rule for flights beyond the pilot's sight, so details can change.

The argument beneath all of this is not settled. In 2011, in a report on government use of drones, the ACLU wrote that cameras on drones raise the prospect of a significant new avenue for the surveillance of American life, and it recommended a warrant whenever a drone would intrude on reasonable privacy expectations, with limits on keeping images of identifiable people. On the other side, the Interior Department says drones gather data safer, at lower cost and with less environmental impact, a sheriff's team found a missing person at night with a thermal camera, and the FAA counts more than 100 reports a month of drones near airports. Each side is describing something real, and neither is wrong about its own facts. Remote ID touches only one part of this: it can find the person flying, and it does not send what the camera sees.

The lift equation holds on other worlds, and one aircraft tested it. On April 19, 2021, NASA's Ingenuity made the first powered, controlled flight on another planet, in air less than 1 percent as dense as Earth's. Density is one term in the equation, so with everything else equal the lift is under 1 percent as large, and only more area, a better coefficient or more speed can make it up. Ingenuity had a mass of 1.8 kilograms, rotors 1.2 meters across, and drew about 350

watts in flight. It flew 72 times. The builder in the parking lot packs up her tools, folds the laptop shut and carries the quadcopter back to the car. Next week, in thicker air, it will fly again.

Questions

1. Why does NASA's lift equation make rotor speed such a strong control?

A. Lift depends on the square of the speed
B. Lift depends on the cube of the weight
C. Lift does not depend on speed

2. In the cascade described, which loop is innermost?

A. Position
B. Rate
C. Velocity

3. In the energy screens, a perfect hover of the example machine needs about how much power?

A. 4.4 watts
B. 440 watts
C. 44 watts

4. In the first screen, a small machine is said to have "so little inertia." Inertia most nearly means

A. the power of the battery
B. the height it can reach
C. resistance to a change in motion

5. Which of these does a Remote ID broadcast module NOT send?

A. What the camera sees
B. The take-off point's position
C. A UTC time mark

6. Why does less dense air matter for Ingenuity?

A. It makes the rotors heavier
B. Density is a term in the lift equation, so lift drops if all else is equal
C. It makes the battery larger

Words to know

inertia: resistance to change
cascade: loops within loops
gyroscope: rotation sensor
oscillation: back-and-forth swing

airspace: regulated sky

Answer key: The Loop That Holds a Drone Up

1. A. Lift depends on the square of the speed
2. B. Rate
3. C. 44 watts
4. C. resistance to a change in motion
5. A. What the camera sees
6. B. Density is a term in the lift equation, so lift drops if all else is equal