The Battery Energy Density Revolution

(and other truths from the world of rotorcraft drones)

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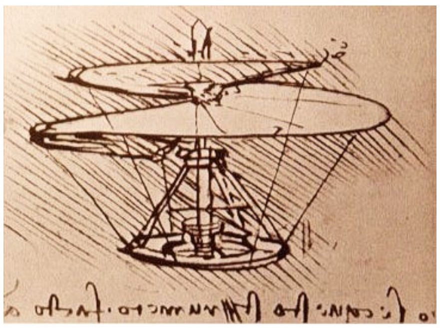
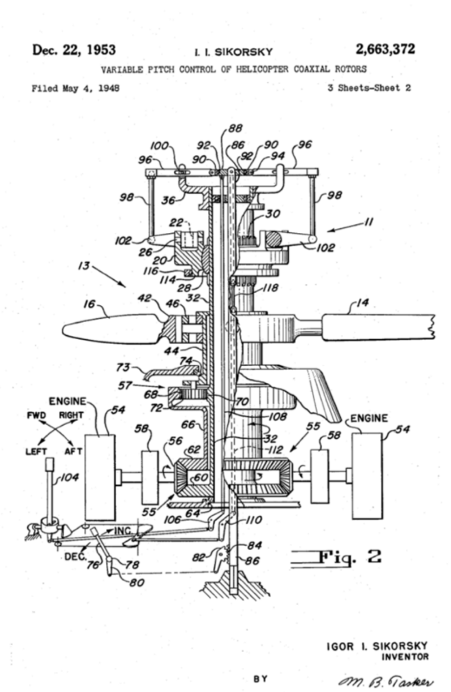


Introduction
Rotorcraft drones are promising but we have a long way to go because of energy production, energy management, and energy storage today. This is particularly true if we want our drones to be anything more than hobby items and platforms for photographing weddings. As we discuss here, the opportunities are endless if we can crack some key systems problems.

Why Rotorcraft?
Rotorcraft are wonderful because they can fly along almost any trajectory, land and take-off vertically from almost anywhere, and hover. It is not surprising that helicopters are extremely popular in applications as varied as military special operations, civilian search and rescue, and transporting people and parts to oil rigs, though they do not have the range of comparable fixed-wing aircraft.

Over the years, multi-rotor rotorcraft such as quadrotors have entered the prosumer and consumer spaces. With advances in sensing and computing, it became easier to control these rotorcraft. In the last five years, we have observed the emergence of a vast number of small, sophisticated multi-rotor aircraft, and a flourishing ecosystem of software, sensors, avionics, controls and services companies. One of them, the Chinese company DJI, is officially a unicorn, valued at several billion dollars. The possible applications are endless: pizza delivery, package transport, mapping, inspection, search & rescue, surveillance, and even people transport. Airbus Group expects over 350,000 air-taxis within 6 years. The future is exciting, and the opportunities are exhilarating. While autonomous cars are all the rage today, autonomous drones, especially multi-rotor drones, have an even greater disruptive potential in the sky.



Electric Flight
Somewhere along the way in the last few years, drones went multi-rotor and electric. Why? We need to invoke a little systems thinking to explain this evolutionary divergence.

A traditional helicopter transmission system is a mechanical miracle. It works for the size and cost of large helicopters but it is too expensive and heavy for smaller devices. Helicopters are also somewhat difficult to control: Lift, forward motion and direction are manipulated through a series of complex actions involving the throttle, collective, cyclic and the anti-torque controls.

So two evolutionary mutations occurred simultaneously. First, drone designers replaced mechanical transmissions with electrical transmissions. Instead of a rotating shaft to deliver power, they used wires, electronics, and direct-drive motors to power the rotors. Suddenly the weight penalty of a mechanical transmission was gone, and there was no incremental penalty from adding additional rotors. Second, armed with electrical transmissions, drones went from 1 rotor (the helicopter) to a quadrotor (4 rotors). Now control became easy – by simply modulating the power to the rotors it became possible to achieve all the maneuverability of a helicopter with simpler controls. This was brilliant. Two problems solved at once.

With electrical power and motors, the quadcopter industry became the preserve of electrical and software engineers. The question that remained was: How do you power an electrical system? The electrical engineer's answer, of course, is batteries. After all, virtually everything today—from the cell phone to the car—now draws its electric power from batteries.

Why Batteries Alone Won't Fly
Cell phones are space limited: They require batteries that can be packed into a device that fits in your palm. Electric vehicles are cost-limited: They require batteries that can give you sufficient range at an affordable lifecycle cost. The weight of the batteries isn't a major issue in either situation, and gravity isn't the real enemy. But gravity is the critical issue in drones.. Unfortunately, batteries won't fly. At least not long enough to be truly useful.

Most battery-powered drones today fly tens of minutes with no payload. But they need to fly for hours with a payload to make a dent in many real applications—whether carrying equipment for inspecting a pipeline or delivering a package to a consumer. The fact is you need a very high specific energy to fly and carry a payload.

Unfortunately, Moore's Law doesn't apply to batteries. Improvements will occur, but only incrementally and linearly. The chasm is too wide to bridge if we want drones to take-off in the next few years. Meanwhile, electric batteries have other problems too. They take time to charge. They require charging stations. They degrade over time. They are expensive. And so on.

Electric batteries are simply no match for traditional gasoline on many fronts. There's a reason gasoline is called "black gold." The next time you fill your tank with gas, marvel at this: There are 11.5 Megawatts[1] of effective power passing through that cold metallic nozzle.[2] While today's batteries have specific energies of approximately 200-250 Wh/kg, electric aviation will need 1000 Wh/kg to succeed. For example, a 1000 kg aircraft that carries a 200 kg payload will require over 140 kW of power. Using the latest and largest battery pack from Tesla Motors, a 100 kWhr battery will weigh about 500 kg, and will give this aircraft 42 minutes of flight time. The battery is half the weight of the aircraft, and two and a half times the weight of the payload. And 42 minutes is simply too short.

Gasoline on the other hand has an energy density of 46 MJ/kg or 12,700 Wh/kg of raw energy. With present technology, we can readily convert this energy to electricity with better than 20% efficiency. And gas tanks can be filled much more rapidly than a battery can be recharged. Therefore, why not combine the gasoline engine and a much smaller battery and have the best of both worlds? This solution fuses the portability and instant power availability of batteries with the high energy densities of gasoline. These solutions are available today and are the immediate future of transportation and aviation systems in the foreseeable future.

	Advantages	**Disadvantages**	**Specific Energy (Wh/kg)**
Batteries	Rechargeable	Low Energy Density	~200-250
	Relatively Cheap	Takes Time to Recharge	
	Reliable	Charging Inefficiencies	
	Available in High Quantities		
	High Power Availability		
	Silent Operations		
Gasoline	High Energy Density	Requires Power Conversion	~12,700
	Readily Available Fuel	Extra Weight for Power Conversion	
	Wide Operating Temperatures	Environmental Pollution	
	Reliable Energy Source	Loud Operation	

Top Flight Technologies: Addressing Energy Density

At Top Flight, we're addressing mobile energy density and power conversion problems from a systems perspective. We are focused on aerospace, defense, and transportation markets that require the highest energy performance, reliability, and productivity. Our goal is to continue perfecting and revolutionizing energy storage and power conversion, and to pioneer energy management methods. While the airframe, propulsion, battery, infrastructure, storage, controls and manufacturing problems can be designed individually, uniting all these questions into a single hybridized system with an engine and a small battery has all sorts of systems

[1] Gasoline = 46 MJ/kg, 15 Gallons = 45 kg, Average 3 minute Fill-up Time; effective power = 46 MJ/kg x 45 kg/180 seconds = ~ 11.5 MW
[2] This is before correcting for the efficiency of gasoline internal combustion engines.

advantages. We have essentially built a Toyota Prius for the sky, and the results are enthralling– range, payload, and speed beyond anything else available. In short, we are having the cake and the eating too.

It isn't easy, though. Building a flying hybrid electric system poses very challenging problems, and our team of MIT scientists and engineers has learned how to address them through 48 grueling months of humbling lessons. In the process, we have solved a number of key problems from battery technology to engines, from power systems to manufacturing—all from first principles. Over the next 5-10 years, we will continue to focus on perfecting energy management, hybrid electric power conversion and high energy density solutions, and empower drones to seize the future.

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