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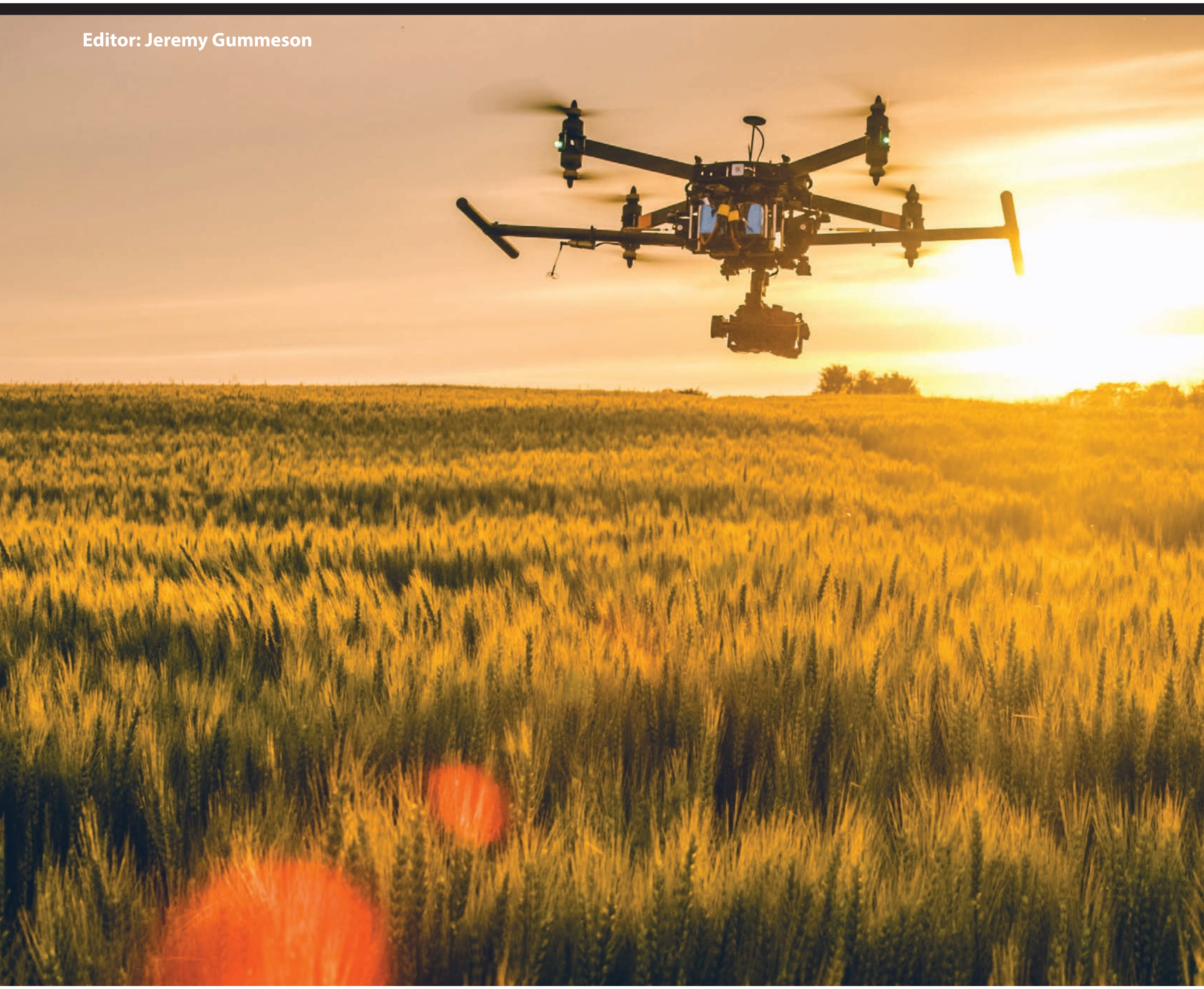

THE FUTURE OF UNMANNED AERIAL VEHICLES (UAVS) HAS NO BATTERIES

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Unmanned Aerial Vehicles (UAVs) hold immense potential across various fields, including precision agriculture, rescue missions, delivery services, weather monitoring, and many more. Despite this promise, the limited flight duration of current UAVs stands as a significant obstacle to their widespread adoption. Attempting to extend flight time by solar panel charging during midflight is not viable due to battery limitations and the eventual need for replacement. This article highlights exciting efforts towards the future of a UAV that survives in the air by harvesting solar energy and performing long-term missions without battery re-charging and/or replacement.

Why Are UAV Solutions Still not Widely Adopted? Battery powered drone technology has become an indispensable tool across various industries; by equipping these tools with sophisticated sensors and cameras, drones can perform in a wide range of applications and tasks, ranging from aerial imaging to spot inspection for otherwise unreachable locations. Proponents of drone technology envision UAV assistance in ever-unfolding facets of commerce, such as drone package deliveries already being tested by Amazon. However, one of the primary limitations of further market penetration is the limited flight times of conventional battery powered UAVs. Even the most popular commercial drone solutions, such as the DJI Maverick 3, have flight times of just 46 minutes before adding auxiliary cameras, sensors, and tools. This is due to the limited energy density of current battery technology; lithium polymer batteries store around 200 Wh/kg [1] and each kilogram of power storage is a kilogram of weight the drone must overcome to fly. With diminishing returns from additional battery weight, other avenues of increasing flight time ought to be explored.

WHAT ARE THE WAYS TO MAKE UAVS FLY LONGER?

In-Flight Charging! Intuitively, we can extend the flight times of drones in general by finding ways to charge their batteries *while* they are flying. Contemporary research focus on energy technologies has led to several promising avenues for extending flight times of UAVs, including harvesting inductive energy from powerlines, wireless charging from ground stations, and applying solar harvesting hardware to the drone's airframe.

Harvest Energy from Powerlines: Typical electrical lines transmit AC power which oscillates polarity 60 times per second under nominal operation, inducing magnetic fields along their entire length. Researchers have recently demonstrated an autonomous multirotor drone equipped with an inductive charging harness that can attach to powerlines in flight and use the magnetic fields induced to charge in the same manner as inductive smart phone chargers [4]. Their demonstration involved a two-hour deployment of their drone, which performed mission objectives alongside managing its charging requirements, autonomously locating and leveraging powerlines of various power classes throughout the deployment. While this represents an exciting and innovative way to extend deployments for autonomous drones, the reality is that the *useful* flight time of the drone over this two-hour deployment did not extend the envelope of contemporary drone flight times; in essence, the autonomous drone was only able to fly for up to seven minutes between lengthy charging cycles for a total of 35 on-mission minutes of flight time over the two-hour deployment. The heart of the problem lies in the small charge/discharge ratio of modern batteries; *it takes longer to charge a lithium-ion battery than it takes to discharge*, and this ratio can vary dramatically depending on the electrical load demanded from the battery and the available power to charge the battery.

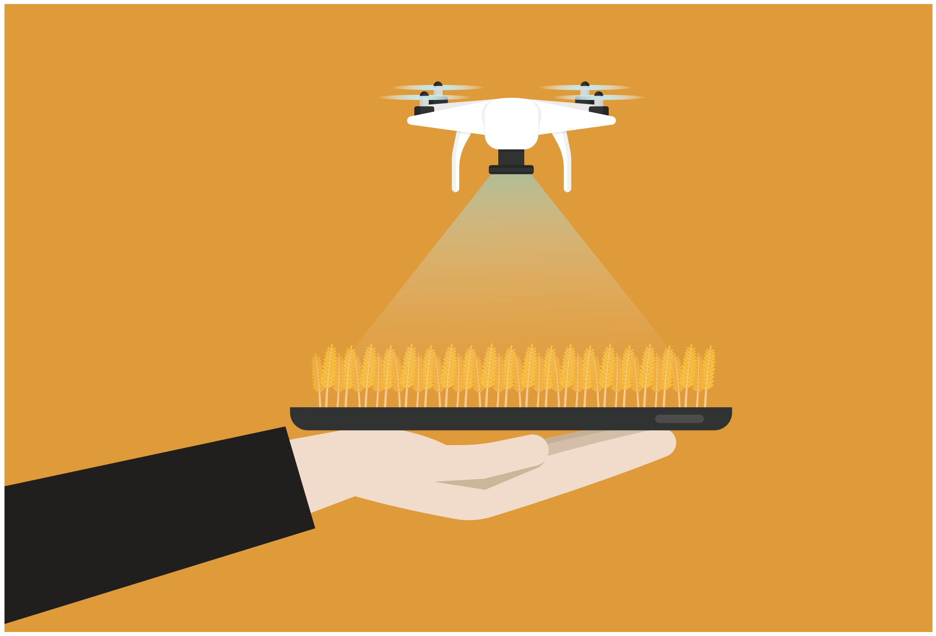
What About Wireless Charging Methods? Wireless power transmission has been in use by the military for nearly a century, but it is generally regarded as a novelty due to the extreme inefficiency of the practice. Using an electrical source to generate high power emissions (lasers, microwaves, etc.) can have an efficiency loss of 15-50% and using a state-of-the-art photoelectric converter to transduce those emissions into electrical energy can have efficiency losses of 50% or more. Still, if the incentive is high enough and the source grid is strong enough, then the technology can be adapted to the purpose. Researchers have prototyped a multirotor drone and the corresponding ground transmission laser, which charges the drone in-flight [6]. The commercial enterprise Global Energy Transmission has created waystations that can be deployed along flight routes to charge drones in-flight [15], but there are many engineering and logistical challenges to overcome before this method can be adapted for mainstream UAVs. Primarily, since wirelessly transmitted power is highly directional, systems to track the UAV and calculate targeting solutions for the emission beam would be required [7,8], and once these solutions were developed, drones would be limited to operational areas inside the effective area of these emission stations.

How About the Obvious Choice? Solar panels seem like the obvious choice for extending flight times in UAVs, and in particular fixed-wing drones are well suited to the application of solar harvesting hardware. Modern solar cells are capable of generating power in excess of 200 W/m^2 [13], and fixed-wing drones have plenty of surface area for solar cell application thanks to their broadly shaped wings. Furthermore, fixed-wing drones make use of aerodynamic advantages that produce more lift than the thrust developed by the main motors, limiting the need for power hungry motors. Many projects have applied solar harvesting to drones to extend the flight times considerably [1,10], but even after solving the engineering challenges associated with in-flight solar energy harvesting, indefinite flight of the UAV will still be limited by the battery. Modern lithium-ion batteries can only recharge around 1000 times before they must be replaced and are highly susceptible to environmental fluctuations in temperature and humidity. Furthermore, batteries can represent as much as 65% of the total weight of a drone, limiting payloads and deployment packages for sensing systems.

The Limiting Factor: All of the considered solutions for extending flight times of UAVs suffer from one common factor: *batteries*. Using batteries to store charge is as natural as putting gasoline in a car's fuel tank, but as a solution for extending UAV flight times batteries simply fall short. First, batteries can comprise as much as 65% of the weight of typical UAVs [14] as discussed, increasing the power needs of the lift systems. Second, as flight times become longer and longer thanks to constant recharging efforts the cost of replacement batteries required due to limited lifetime charge cycles will grow. Third, the electrochemical reaction that produces electricity inside of batteries is highly dependent on temperature, limiting the operational ceiling of UAVs due to atmospheric cooling or requiring dedicated temperature maintenance systems on the drone. And finally, once these batteries have lived their useful lives, they become harmful waste that is burdensome to dispose of properly. The solution to this issue is simple: remove the battery entirely. A purely solar-powered UAV offers a compelling solution to address the limitations of battery-powered UAVs. Solar UAVs would integrate solar panels into their wings and contain the hardware to generate electricity efficiently and continuously from sunlight, significantly extending their endurance and operational range by forgoing the cumbersome battery in favor of a capacitor array to buffer charge. This UAV would be free from operational constraints that limit mission areas to locations with infrastructure like power lines and emission stations; anywhere the sun was shining, this drone could fly.

The Possibilities of All-Day Flight: By extending flight time, battery-free UAVs will enable longer missions like forest wildlife censusing, search and rescue, and precision agriculture. More specifically, commercial farms in the States operate upon many thousands of acres of crop fields and, with the advent of precision agriculture, it has become common for such farms to deploy constellations of sensing equipment to monitor their crops. Depending on the constellations, it may be necessary to reside in close proximity to connect to the sensors and download their data payloads; however, with larger facilities this can become a burden preventing practical deployment of these constellations. Battery-powered UAVs have seen some success in solving this problem but fall short due to their limited flight times whereas a single battery-free UAV could sustain half-day deployments, visiting each critical constellation node and

THIS ARTICLE HIGHLIGHTS EXCITING EFFORTS TOWARDS THE FUTURE OF A UAV THAT SURVIVES IN THE AIR BY HARVESTING SOLAR ENERGY AND PERFORMING LONG-TERM MISSIONS WITHOUT BATTERY RE-CHARGING AND/OR REPLACEMENT



Illustration, istockphoto.com

loitering as long as necessary to download the data payload without concern for critical battery stores. Where dozens of battery-powered UAVs *might* suffice, a single battery-free UAV would shine. This would be true of other applications; monitoring air-quality in cities could be done with a single drone outfitted with the right sensors, wildfires could be tracked in real time by a drone with GPS and infrared cameras, the list goes on!

Sounds too Good to be True… And for now, it is. Realizing this UAV presents several technical challenges that would need to be addressed:

1. Buffering solar energy without batteries is difficult. Typically, any power produced by a solar array can be pushed directly into the charge controller of a battery; however, batteries are not allowed and the technology to efficiently charge capacitors from solar panels will need adaptation.

2. Modifying every UAV airframe for a battery-free approach will not be feasible. Multirotor UAVs can have high power requirements and low real-estate for solar panel deployment. Selecting the right airframe will be key.

3. Any battery-free UAV will need to be tolerant to intermittent power events. Solar panels operate most effectively when they receive solar radiation directly normal to their surface. Because any UAV will need to maneuver in several orientations during nominal flight, techniques to mitigate power failures due to poor maneuvering choices and other intermittent events must be developed.

CALL FOR ACTION

The challenges outlined above must be overcome to create a truly robust and long-lived battery-free UAV. Below, we outline our current understanding and state-of-the-art solutions for these exciting research directions.

1. To adapt charge controllers for capacitors, it is necessary to understand the power behavior of solar panels. Solar cells tend to exhibit a linear relationship between output voltage and load current; however, at the upper limit of output voltage the load current "knees" downward, reducing overall power output dramatically. This behavior presents a challenge to extract the best possible power from the solar cells by choosing a load current that aligns with the maximum power point on the voltage-current curve. It is possible to design a circuit to detect the maximum power point automatically and adjust the load current accordingly, but the load current of a charging capacitor varies dramatically depending on its charge state. Furthermore, a bank of capacitors buffering charge for the UAV may experience varied charge rates due to manufacturing inconsistencies, which could lead to overvolting individual capacitors and damage to the circuit. Efforts will need to be made to design circuitry capable of efficiently charging and protecting the buffer capacitors for the battery-free UAV.

2. A typical brushless DC (BLDC) motor can require as much as 100 W of power to operate normally, and multirotor drones typically have four or more of these BLDCs. To accommodate the power requirements of these motors, at least 2 m^2 of solar panels will be needed. This real-estate typically does not exist on multi-rotor drones and could not be added without significant airframe modification. Fixed-wing drones, however, offer the needed surface area without modification, and that surface area serves dual purpose. Applying solar panels to wing shapes can be a truly synergistic solution for the battery-free UAV, but there are still many airframes to consider when selecting from fixed-wing designs. NASA's Centurion, for example, was a flying wing airframe, but conventional airframes may offer the needed wing area while also retaining other advantages. This will require iterative ideation and prototyping to find the best fit for the battery-free UAV.

3. During normal flight operations, a UAV will experience variance in solar radiation due to the pitching of the nose, the rolling of the body, and even natural changes in cloud cover. All of these can contribute to an intermittent power event, where the power generated by the solar harvesting circuit does not meet the demand of the UAV. Without hardware to detect these events and software to manage them, power failures will lead to loss of communication with the UAV, motor failure, and rapid unplanned disassembly. Making use of analog-to-digital converter modules, the power state of the capacitor buffer, solar array, and flight control systems can all be monitored for an intermittent power event. If any of these power parameters fall below a set threshold, a software routine may engage to take corrective action. Using a standard 32-bit microcontroller, a low-

power flight controller platform could be implemented to manage power and state parameters during flight. By adding a compatible GPS system, such a UAV could even be flown autonomously. Then, so long as the UAV could support the added weight, an all-day aerial sensing platform could be deployed for purpose-built studies to monitor air quality, perform aerial surveillance, and more! An entire branch of intermittent control system computation will be opened by the battery-free UAV. Algorithms for managing intermittent events would evolve alongside machine learning for edge devices, morphing into predictive models for anticipating low-power periods based on weather. Actuators designed to be intermittently powered can lock control surfaces into configurations meant to induce best possible glide. ■

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