2022 International Conference on Unmanned Aircraft Systems (ICUAS)
Dubrovnik, Croatia. June 21-24, 2022

A Lightweight Device for Energy Harvesting from Power Lines with a Fixed-Wing UAV

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***Abstract*— Modern UAVs (Unmanned Aerial Vehicles) suffer from restrictions in flight range and time due to battery capacity limitations. One way to overcome these limitations is to harvest energy from overhead power lines. A growing body of scientific literature has documented the development of energy harvesters on multirotor UAVs. However, to date, there have been no implementations on a fixed-wing UAV. In this paper we build upon a previously developed passive perching mechanism for fixed-wing UAVs by incorporating into it a split-core transformer for energy harvesting. We validate the perching mechanism as well as battery recharging in a realistic outdoor environment. We find that a minimum speed of 1.25m/s is required to successfully perch on the power line. This is below the stall speed of the UAV used in this project. Furthermore, experiments verified that no damage was done to the power line during perching, as the induced forces were equivalent to 1m/s wind gusts. Characterization of the energy harvesting shows that with a maximum of 3.3W of power from the harvester, we can fully charge a 2200mAh battery in 2.2 hours. Weighing only 420g, our device is the lightest energy harvester developed to date.**

I. INTRODUCTION

Unmanned Aerial Vehicles (UAVs) are increasingly being used to inspect large scale infrastructure [1]–[4]. This is especially true for electrical infrastructure, where UAVs are uniquely able to safely approach the potentially dangerous high-voltage overhead lines [5]. However, by their nature, power grids are vast, widespread networks of hardware. UAVs that are used for inspecting or maintaining them need to travel long distances over long periods of time. Small scale multirotor (and to a lesser extent fixed-wing) UAVs do not have the range and endurance to perform their mission, and return [6].

To overcome this problem, researchers have been developing technologies to take advantage of the high-voltage lines themselves to recharge UAV batteries [7], [8]. This has worked well with multirotor UAVs which can hover, and slowly raise or lower themselves onto the overhead line and begin recharging [9], [10]. Fixed-wing UAVs generally cannot hover, and thus will need an alternative strategy to perch on power lines. Recent developments in fixed-wing perching have shown that passively closing claws can be used to perch on rigid structures without the need to hover [11], [12].

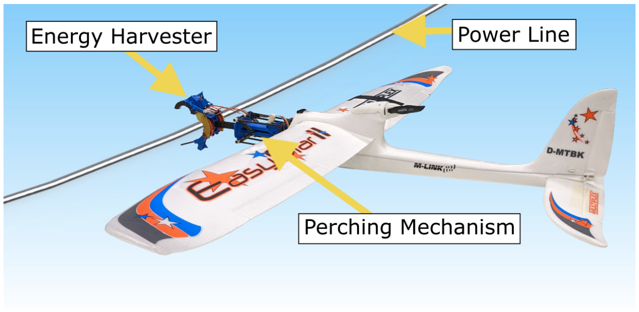

Fig. 1. Photograph of UAV with energy harvester mounted on the nose.

In this paper, the methods used for fixed-wing perching are combined with recharging devices developed for multirotors. Our solution is a newly developed passive perching device which is mounted to the nose of the aircraft (Fig. 1). It consists of a latch for holding onto the overhead line and two split-core transformers for recharging. As the aircraft hits the overhead line, the latch closes and the aircraft hangs from it. Once the UAV has settled into a position hanging from the power line, servos bring the split cores together into a complete ring. On-board electronics are then used to convert the alternating current of the power line to recharge the UAVs battery. We characterize two aspects of our solution, the mechanical perching capability and the electrical recharging capacity. Our devices performance is then compared with previously developed solutions.

The main contributions of this work are the following:

1) A novel mechanism for passive fixed-wing UAV perching incorporating on-board battery recharging with the lightest harvester installed on a UAV to date.
2) Characterization of perching performance on cables and comparison with similar perching mechanisms on rigid structures.
3) Validation of our prototype in a realistic, outdoor, overhead power line cable.

The rest of the paper is structured as follows. Section II reviews the relevant related work. In Section III we conduct a design space study for the most important metrics for the energy harvester. Section IV covers the characterization of perching performance and Section V covers the characterization of the energy harvesting. Finally, Section VI discusses the conclusions and future work.

This work was supported as a part of NCCR Robotics, a National Centre of Competence in Research, funded by the Swiss National Science Foundation (grant number 51NF40_185543), and the European Union's Horizon 2020 research and innovation programme under grant agreement ID: 871479 AERIAL-CORE *(Corresponding Author: William Stewart)*

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II. RELATED WORK

Utilizing overhead power lines for recharging UAVs has been of interest to the scientific community for quite a while [13]. Focus has been primarily on the implementation of energy harvesting on multirotor UAVs due to the simplicity of the approach maneuver. The hovering capability of multirotor UAVs enables them to lower or raise themselves to the overhead line, rather than having to perform some complicated maneuver to get onto the line. This means that researchers could focus on the energy harvesting aspect.

One of the first solutions to be proposed was a wireless charging platform that can be attached to the overhead lines to enable a UAV to directly charge its batteries [13]. When combined with wireless charging technologies, this solution is a simple and easy to implement technology [8]. However, it requires preinstalled infrastructure to work and limits the locations where the UAV can charge. Having set harvesting locations also requires more complicated mission planning.

Another solution is to implement the recharging device directly on the UAV itself [14]. Kitchen et al. developed a U-shaped core transformer and attached it to the top of a multirotor. The vehicle would align itself under the power line, then rise up until two hooks could be activated to grasp the power line. Then the mechanism pulls the aircraft up until the power line rested in the U-shaped core. The total weight of the device was just over 3kg and it was able to draw up to 1W of power from the power line. However, the U-shape of the core results in a low power output.

Vom Bögel et al. proposed an alternative design using a split-core transformer that closes around the power line as the UAV lands on the line [7]. The authors showed that they could extract up to 51W of power with their 700g magnetic core. This is considerably higher power for a lower weight then that of Kitchen et al. Nevertheless, 700g is still a considerable weight for small-scale UAVs that weigh on the order of 1kg.

By utilizing multirotor UAVs, the previously discussed works have simplified the problem of energy harvesting to just the electrical aspect. However, to expand the harvesting technology to fixed-wing UAVs new solutions will need to simultaneously address both electrical considerations as well as the perching. This is because fixed-wing UAVs cannot hover, and therefore must maintain some horizontal velocity right up to the point of perching. VTOL (Vertical Take-Off and Landing) UAVs could in principle be equipped with the same harvesters as used with multirotors, but doing so requires the use of heavy and complicated VTOL mechanisms in addition to the weight of the harvester.

The most common perching techniques for fixed-wing UAVs have used a pitch up maneuver, which slows the UAV down considerably just before touch down [15]. One foundational work on the topic even employed this maneuver to perch on a cable [16]. The drawback to this approach is that the pitch up maneuver puts the UAV in a dangerous position as it is forced to operate close to stall where the control power is reduced.

Recently, the authors have demonstrated a passive perching mechanism that uses a claw to perch on bars and rods [12]. This mechanism reduces the complexity of the perching maneuver by streamlining it to simply flying into the structure at the minimum speed required to maintain flight. By doing this, the UAV can avoid the dangerous pitch up maneuver implemented by others. After perching, the airplane hangs vertically from the bar. This system also includes passive energy recapture and storage through an auxiliary locking mechanism which stretches four linear springs at impact, and can use the energy in them to reset the perching mechanism once in flight again.

While the previously developed claw is effective at perching, it does not hold the UAV close enough to the power line for the split-core transformer to fully envelope the high voltage power line. To overcome this, we developed a new mechanism that utilizes a latching mechanism, similar to those commonly used in doors. Latches have been used previously with UAVs to secure parcels for delivery [17]. The focus of that work was a holistic view of an entire UAV-based delivery system consisting of an autonomous multirotor, navigation planning, and interaction through a smartphone app. As a result, they did not discuss much on the mechanism they used.

III. MECHANISM DESIGN

In addition to the latch for perching, this work includes an energy harvester that consists of two split-core torodial transformers (Fig. 2). One half of each toroid is wrapped with loops of copper wire and rigidly fixed to the mechanism. The other halves are each connected by hinges and can close around the power line. The transformers constitute the bulk of the weight of the harvester and their design parameters heavily influence the recharging performance, so the design process began by considering the harvester components.

A. Transformer Core Material Selection

To keep weight as low as possible, a material trade study was conducted. Three aspects of the design were considered, brittleness, recharging performance, and weight. Low brittleness is required to reduce the chances that the core will crack or chip at impact. Minimizing losses from eddy currents and hysteresis will result in a more efficient harvester, while high permeability will proportionally increase the induced voltage in the harvester. Keeping weight low will mitigate the overall degradation in flight performance of the UAV resulting from the addition of the harvester.

Two materials commonly used in transformers are soft ferrites and laminated electrical steel. In terms of brittleness, the soft ferrites perform worse. They are prone to chipping and cracking, which makes them difficult to work with as well as making them vulnerable to impact damage [18]. The laminated electrical steel reduces eddy current losses and have a permeability on the order of 10^5. Soft ferrites have a smaller permeability (10^4), however, they are lighter (density of $\approx 5\text{g/cm}^3$ instead of $\approx 7.5\text{g/cm}^3$) [19]. Ultimately, on the basis of lower weight, the cores used in this project

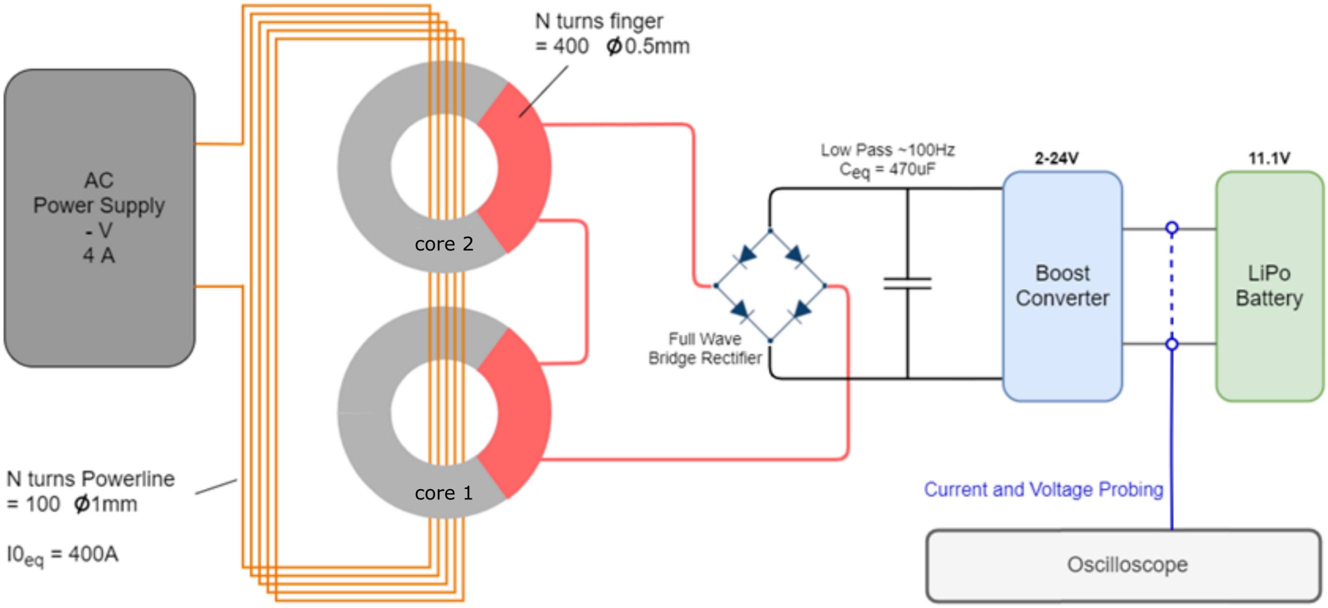

Fig. 2. Electrical diagram of the energy harvester.

were made of soft ferrites. Whole cores were purchased, and carefully cut in half for use.

B. Transformer Core Sizing

Two primary design considerations exist for sizing the split core transformers, weight and electrical performance. Larger cores will induce a higher voltage, and therefore output a higher power from the energy harvester, which will charge the battery faster. However, the larger cores will induce a higher weight penalty on the aircraft. Thus, a balance between low weight and high electrical performance is desired.

To explore the tradeoff space between these two metrics, we calculate the voltage induced on the coil by the power line. This voltage is a function of the material properties of the core, electric current properties from the power line, and the geometry of the transformer core. We use the following equation from [20]

$$V_{ind} = N\mu t R_i \ln(1+w/R_i) f_{elec} I_0 L \tag{1}$$

where N is the number of turns, μ is the relative effective permeability of the core material, t is the thickness of the core, R_i is the inner radius of the core, w is the width of the core, f_{elec} is the frequency of the AC in the power line, I_0 is the current in the power line, and L is an estimated loss factor. The weight of the harvester is only a function of the geometry of the core, so we only investigate the effect of changing t, R_i, and w on the induced voltage (V_{ind}). The non-geometric parameters used in these calculations are given in Table I. The geometric parameters were each varied between 1 and 100mm. Fig. 3(a) plots the results of equation 1. The calculation shows that varying the inner radius of the core does not produce significant changes in the induced voltage. However, increasing the thickness or width will dramatically increase the induced voltage. To understand the associated weight costs, we calculated the mass of the cores

$$m = \rho * \pi((R_i+t)^2 - R_i^2)w \tag{2}$$

where ρ is the density of the soft ferrite. The solutions to equation 2 found using the same range of geometric parameters are plotted in Fig. 3(b).

Roboticists can use the relationships reported here to determine the core dimensions which will produce the shortest battery charge time, while keeping the UAV endurance as high as possible. For this project a core thickness and width of 13mm and inner radius of 18mm was used. This inner radius enables the perching mechanism to be used on power lines with a diameter of up to 3.6cm. Typical power lines range from 1cm in diameter for low voltage power lines up to about 5cm for high voltage power lines. These dimensions gave a relatively lightweight core of 120g and V_{ind} of 1.75V. The two cores combined with the associated electronics and mechanical parts added up to a total of 420g for the entire harvester.

TABLE I
INDUCED VOLTAGE CALCULATION VARIABLES

Variables	**Value**	**Units**
N	400	N/A
μ	6.3e-3	$\frac{\text{kg}-\text{m}}{\text{A}^2\text{s}^2}$
f_{elec}	50	Hz
I_0	400	Amps
L	0.54	N/A

C. Electro-Mechanical Design

There are two mechanical components to the perching mechanism (Fig. 4). The first is a latching mechanism, which is mounted to the palm of the device. The latching mechanism is used to hold onto the power line. It consists of

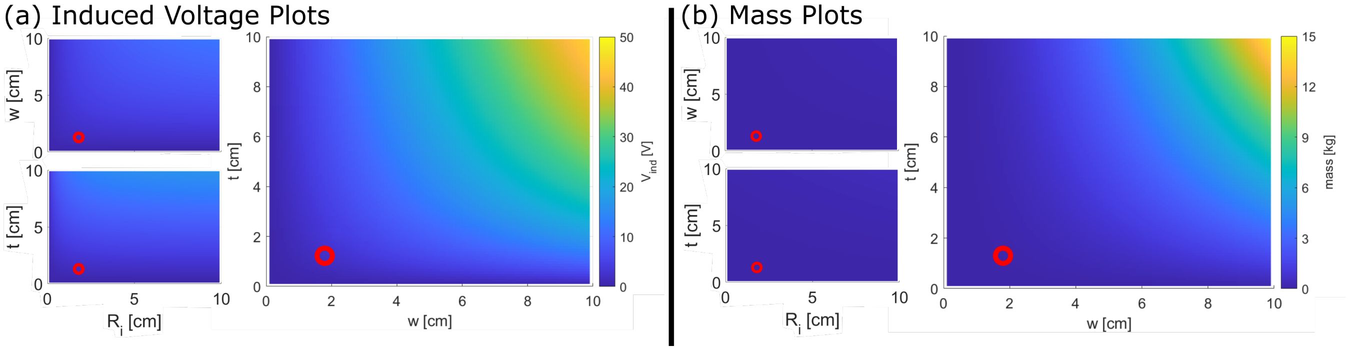

Fig. 3. Plots showing the results of the core sizing study. (a) Plots showing the voltage induced in the coil from the power line (V_{ind}) as a function of the core geometry. The plots on the left show that the inner radius (R_i) of the toroidal core has little effect on the induced voltage, the plot on the right shows that the thickness and width (t and w) of the core have a large effect on the induced voltage. The core sizing used for this paper is indicated with a red circle. (b) Plots showing the mass of the transformer as a function of the core geometry. As with the induced voltage, there is little effect from varying the inner radius (plots on left), and more of an effect due to the thickness and width (plot on right). Once again, the red circle indicates the core used in this paper.

a high stiffness rotational spring which drives a bar to close. A spring loaded latch allows the bar to pass, but blocks the bar from reopening. While approaching the perch location on the power line, the latch is held open by a latch cable attached to a DC motor. At impact, the palm is pushed afterwards, which slackens the latch cable. The slack latch cable allow the bar to close, and the latch locks it in place. Positioning and sizing of the latch was set such that the latch will lock when perching on power lines up to 3.3cm. This is slightly smaller than the 3.6cm inner diameter of the toroidal core, as the palm takes a little space and prevents the power line from directly hitting the ferrite core.

As the palm slides backwards, four linear springs are stretched until triggering a locking mechanism, the second component of the perching mechanism. The purpose behind these linear springs is to absorb some of the kinetic energy from the impact and thereby reduce the forces transmitted to the airframe. The locking mechanism prevents the vehicle from simply bouncing off the power line. Once the locking mechanism is triggered, the linear springs are held in their stretched position, thereby storing kinetic energy from flight as potential energy. When the battery is fully charged and it is time to unperch, the split cores are opened, then the motor is commanded to pull the latch cable, releasing the bar (Fig. 5). The UAV is unstable when flying backwards, so as it falls, it will passively reorient before flying off again. The locking mechanism can then be released, resetting the perching mechanism for the next perch.

The required height for unperching was estimated using the method described in [12]. The height estimate consists of a combination of experimental data and analytical calculation. The drop height required to rotate 180° to a nose down position was experimentally measured to be 5.1m. Further distance is needed to pull out of the nose dive, for that the following expression is used,

$$R = \frac{Vel^2}{gn} \tag{3}$$

where Vel is the velocity, g is the acceleration due to gravity (9.81 m/s^2), and n is load factor, the ratio between lift and weight. This work uses the same aircraft as [12], but with the new perching mechanism with energy harvester. Therefore we use the same lift and experimental data, but with a new load factor n. The lift in [12] is reported as 7.35N, and with the 420g harvester here, this gives a load factor of 0.88. Combined with the experimentally measured Vel of 5m/s, this gives an R value of 3.4m. Adding this to the 5.1m experimental drop height gives a total estimated drop distance of 8.5m.

Parallel to the latching mechanism are the two split toroidal cores. Each toroidal core is split in two, one half is wrapped in wire, the other half is not. Our system consists of two split cores, thus two halves are wrapped in wire and two corresponding halves are not. Following the method in [21], we selected 400 turns of 0.5mm copper wire. The wrapped halves are mounted to the palm. The unwrapped halves were mounted to 3D printed core mounts that connect via a hinge to the palm. Servos are used to open and close the two pairs. When closed, each toroid encompasses the high-voltage line.

The AC from the high voltage line (so called primary current) induces AC in the 400 turns of the copper wire (Fig. 2). This wiring is connected to the main electronics board, which consists of a full wave bridge rectifier, (converts the current from AC to DC), a 470μF capacitor (smooths the signal and reduces noise), and a boost converter (to adjust the current so it matches the current required to charge the battery).

IV. MECHANICAL CHARACTERIZATION

To ensure that the passive perching mechanism will always trigger, the minimum impact speed to trigger the device must be lower than the minimum speed of the UAV. For the UAV used in this work, that minimum speed is the stall speed, which is about 7m/s. We characterize the minimum speed required to trigger the mechanism by hanging the airplane from a pendulum and swinging it into the cable (Fig. 6). The speed of the UAV at impact can be adjusted by releasing it from a variety of heights, or by giving it a push when releasing it. To ensure a realistic environment, we use the outdoor overhead power line test setup at the SDU UAS

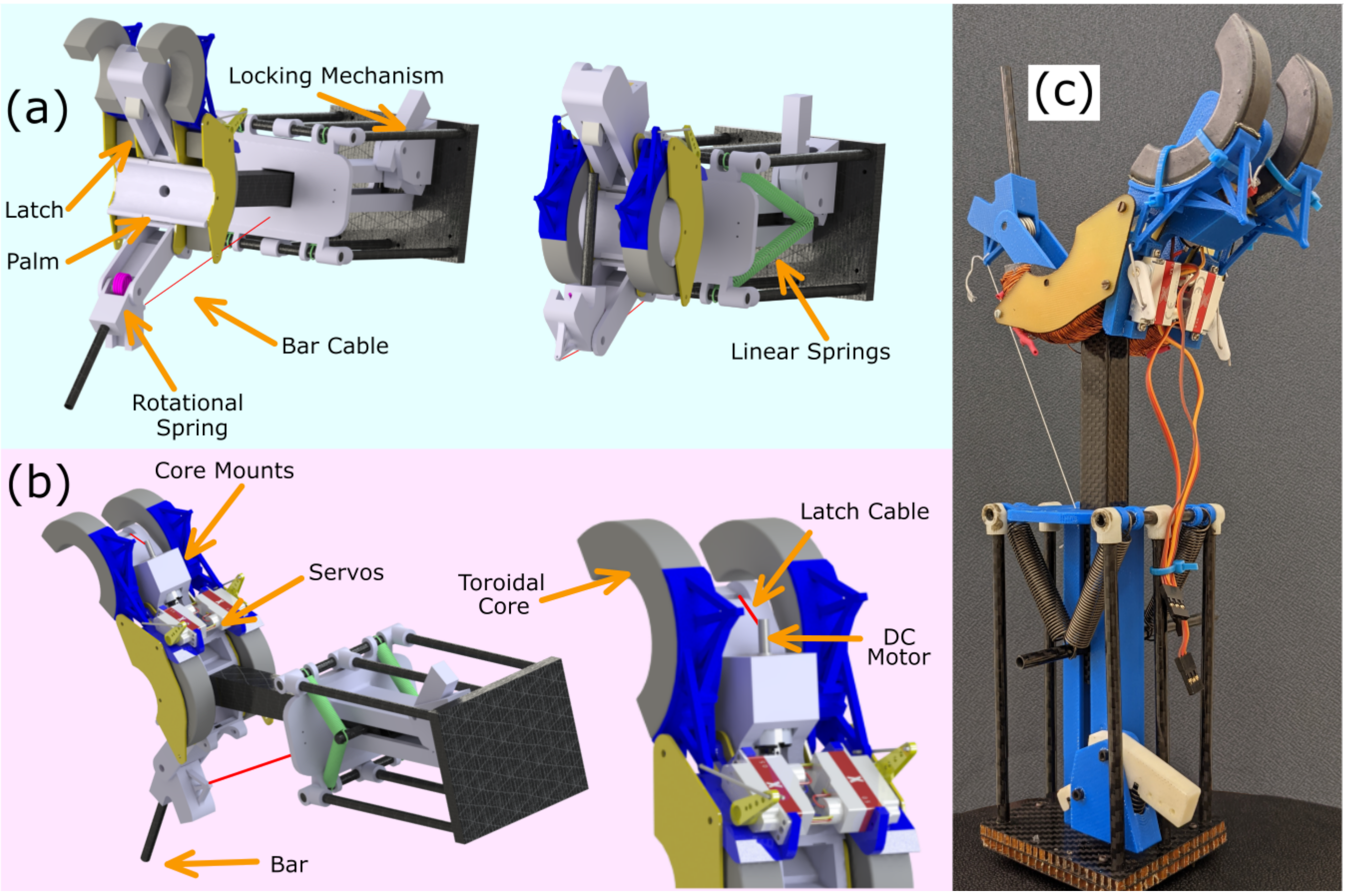

Fig. 4. Diagram of the energy harvester. (a) CAD rendering showing the mechanism before and after perching (left and right respectively). (b) CAD renderings of the back of the mechanism just prior to perching. (c) A photograph of the perching mechanism with recharging transformers.

Center in Odense, Denmark [22]. At this test center there are two towers in a 3-phase setup with overhead power lines, one phase at 3m above the ground, and the second 5m above the first. We strung a rope for the pendulum over the top overhead power line and hung the aircraft on it. The pendulum was located 17m from each tower (the middle of the power line). The opposite end of the rope was anchored to the ground. The pendulum length was adjusted until the perching mechanism was aligned with the bottom power line. Testing was done in fair weather with light gusting winds. Data recording was done using two Bosch SCD110 Sense sensors. The sensors contain 3D accelerometers and can connect to a mobile phone through bluetooth. Data was collected at a sampling rate of 1.6kHz. One SCD sensor was attached to the belly of the aircraft, and a second was attached to the power line in close proximity to the perching point.

A total of six experiments were conducted, five of which resulted in a successful perch, equivalent to an 83% success rate. Data from the accelerometer mounted to the UAV was used to identify the moment of impact. This was easily identifiable as a sharp spike in the acceleration. Data from just before the impact was then integrated to find the magnitude of the velocity at impact (trial 1-6 squares in Fig. 7). The impact velocity varied between 1.1m/s and 1.7m/s throughout the tests. The impact at 1.1m/s did not result in a successful perch. We compare this with data reported on the previously designed claw for perching on rigid structures. The perching mechanism described here has a lower speed threshold for success than the previously developed claw. A few factors contribute to this. The first is that the mass of the mechanism here is considerably higher than the mass of the previous claw (420g instead of 61g). This means that the current design can reach a higher kinetic energy at a lower speed than the previous claw. The second is that the current design uses softer springs in the locking mechanism (120N/m instead of 208N/m). This was done to ensure that the mechanism would function on the cable, which is not as rigid as the bars and rods that the original claw was designed for. Indeed, the fact that the power line is softer than the rigid structures the previous claw was used on implies that the threshold velocity at impact would be higher for the current design than the previous claw because the cable could dampen the impact. However, the data indicates that the softer springs and higher weight of the current design overcomes the more compliant perching structure. The differences between the previous claw and the current mechanism result from different perching scenarios, both perform well in their respective applications. Further analysis on the linear spring design parameters can be found

Fig. 5. Unperching Sequence. On the left, the mechanism configuration while recharging battery. In the middle, the split cores opened. On the right, the latch has been released, causing the bar to open and the UAV to fall.

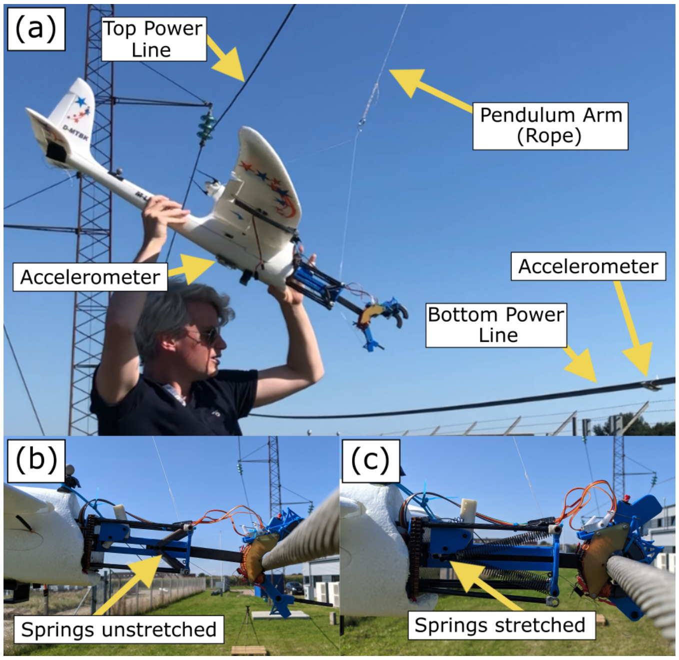

Fig. 6. Setup of the swinging experiments. (a) An overview of the experiment showing the pendulum arm, the location of the accelerometers, and the aircraft. (b) Image of the UAV just before impact with the linear springs unstretched and the locking mechanism open. (b) Image of the UAV just after impact with the linear springs stretched and the locking mechanism closed.

in [12].

Data from the accelerometer mounted to the overhead power line was used to understand the effect of the impact on the power line itself. We then compare the effects of the impact to the effect of perpendicular wind on the transmission line (a common design factor [23]). The dominant aerodynamic effect on transmission lines comes from vibrations induced by vortex shedding. We use a fast-fourier transform (FFT) on the accelerometer data to identify the dominant vibration frequencies induced at impact. These frequencies can then be compared with vibration frequencies induced by wind on the power lines. The equivalent windspeed can be found using the following formula from [24]

$$V = (f_{imp} d)/1.9 \tag{4}$$

where f_{imp} is the frequency of wind-induced vibrations, d is the diameter of the cable, and 1.9 is an empirical aerodynamic coefficient. Using d=20mm and the dominant frequencies from the FFT (each under 10Hz) gives an equivalent wind speed of 1.05m/s. We can therefore say that an overhead power line that is designed to survive wind speeds above 1.05m/s will not be damaged by vibrations induced by the impact of the UAV. This is well below the 12m/s that can cause structural damage [23].

The experiments were conducted at the center of the power lines, away from the support towers. This is because operating in the vicinity of the support towers is dangerous. Near the towers there is the possibility of collision and damage to the towers, or inadvertently bypassing the insulators protecting the tower and shorting the high voltage electricity through the tower. Additionally, the angle of the power lines with respect to the ground increases as they reach the tower. This means to perch on the power lines, the aircraft would have to hold a bank angle, which could complicate the approach maneuver. Nonetheless, we wished to understand if there were any notable differences in perching performance closer to the tower than in the middle of the line. In the vicinity of the tower, the power line is held more rigidly. There should be a decrease in the speed required to successfully perch, which is what we see (trials 7-8 in Fig. 7).

V. ELECTRICAL CHARACTERIZATION

To replicate a high voltage power line, a benchtop setup similar to [7] is used to characterize the energy harvesting. A loop of wire consisting of 100 turns of 1mm diameter wire was connected to an AC power supply. Two cores were attached to the loops and the power was turned on. An oscilloscope read the current and voltage between the boost converter and the battery of the UAV.

Throughout the experiment we varied the current from the AC power supply and measured the power output from the recharging mechanism. Currents that were tested ranged from 100 to 400A. For reference, power lines typically carry between 200 and 1500A. The maximum power output from the system was 3.3W (Fig. 8). This is not as high as the measured power from Iverson et al., however, that energy harvester had much larger cores, and therefore it weighed more as well [25]. Also included is data from Kitchen et al. [14]. As can be seen this harvester has a higher power

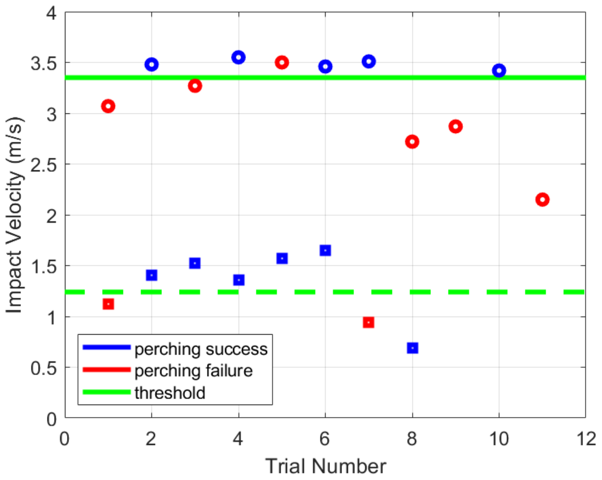

Fig. 7. Results of the swinging experiments. Blue symbols indicate a successful perch, red symbols indicate an unsuccessful perch. Circles indicate data from [12], and squares indicate data from the current experiments. Green lines approximate a threshold of success velocity. The solid green line is for the data from [12], and the dashed green line is for current experiments.

output than the harvester described by Kitchen et al., as well as a smaller mass. This is due to the toroidal shaped of the transformers used here. With a 3.3W power output, the current supplied to the battery is 1A. This would charge a 2200mAh battery in 2.2 hours.

How closely the split cores are connected together can have a large effect on how efficiently the device can harvest power. To quantify this, we ran the same experiment one more time, however, thin sheets of paper were placed in between the split core halves to separate them. We tested a range of gaps from 0 to 1mm and measured the decrease in output power from the system. The tests were conducted at a constant 400A current. The results show a very small decrease in power, up to 12%, being delivered to the battery. This is a promising finding, as it means that the precision and accuracy with which the components of the harvester are built is not a big factor. So long as the various imperfections resulting from construction or wear-and-tear are less than 1mm, the device will still harvest at 88% efficiency.

Indeed, this data is on the conservative side of a realistic scenario, as it completely separated the cores with the paper. In many cases, imperfections won't prevent the cores from coming in contact, but rather misalign them, reducing contact area. In these cases, the losses won't be as great as the constant air gap measured here. Furthermore, when being energized by the power line, a magnetic force is generated between the cores [26]. This force will work to hold the two core halves together, reducing losses that may result from jiggling or temporary separation of the two core halves. The presence of the magnetic force drawing the cores closed means it may be possible to use soft materials to build the mechanism. A compliant mechanism could potentially better absorb impact forces as well as conform to the power line. Soft materials do not perform well when exerting high forces, but high forces are not needed to hold the cores together when the magnetism can do the job.

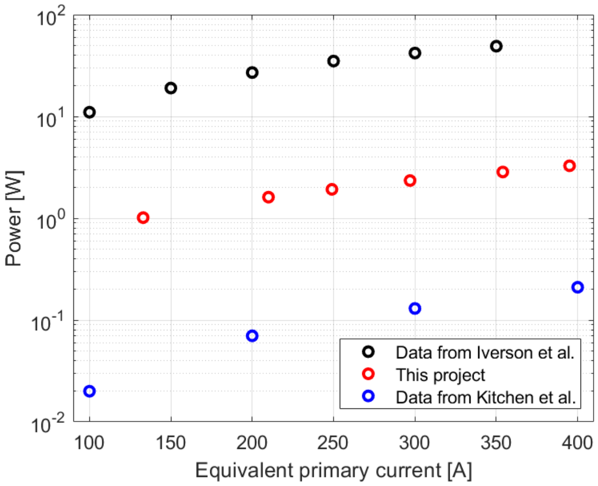

Fig. 8. Data from the electrical characterization tests. Plotted alongside the results from this project are experimental results from other projects, Iverson et al. [25] and Kitchen et al. [14].

VI. CONCLUSIONS

This work has demonstrated the first fixed-wing UAV to conduct charging on power lines. We accomplished this through the combination of a passive perching mechanism and split core transformer. The energy harvester is able to draw up to 3.3W while weighing only 420g; the lightest UAV harvester reported in the literature to date and can charge a 2200mAh battery in 2.2 hours. We validated the prototype in a realistic environment showing that with a minimum speed of 1.25m/s, the mechanism can successfully perch on a power line. This study does not directly address the added mass of the harvester on stability. In general, adding mass to the nose of the aircraft increases the stability margin, but requires flying at a higher angle of attack, leading to increased induced drag. When implementing the design, careful placement of the CG (such as positioning the battery farther back) will diminish this effect. This is often done on fixed-wing aircraft whose engines are positioned at the nose of the vehicle. The proof-of-concept mechanism developed here additionally adds aerodynamic drag. The effect of this will be reduced in future work through the implementation of a clam-shell faring around the harvester that can be opened just prior to perching. In addition, future work will address potential problems arising from harvesting power for long periods on the power line. These could include twisting around in higher winds as well as vibrations due to AC current and temperature changes that can cause wear and tear on the split cores. Power line tracking and following systems will continue to improve [27], and once they are mature enough, they can be combined with energy harvesters developed using the findings of this work.

The novel energy harvester built as part of this project will serve as the starting point for future fixed-wing UAV energy harvesting projects. We have shown that split core transformers can be made small enough and lightweight enough to install on small scale UAVs, opening the door for more designs and implementations. Future projects will study ways to mitigate the added drag from the device structure as well as demonstrate it's function at high speed.

VII. ACKNOWLEDGEMENTS

The authors are grateful for the engineering help provided by Pierre Groslambert and Olexandr Gudozhnik.

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