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Design and Evaluation of a Perching Hexacopter Drone for Energy Harvesting from Power Lines

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Abstract— **With a growing number of applications in the world for UAVs, there is a clear limitation regarding the need for extended battery life. With the current flight times, many users would benefit greatly with an innovative option of field charging these devices. The objective of this project is to investigate feasibility of inductively harvesting energy from a power line cable for applications such as charging a UAV drone. Research investigates a dual hook perching device that securely attaches to a power cable and aligns an inductive core with the cable for harvesting energy from its electro-magnetic field. Modeling and analysis of the core highlights critical design parameters, leading to evaluation of circular, semi-cylindrical, and u-shaped prototypes designed to interface with a 1" power cable. Underactuated two jaw manipulators at each end of the coil are proposed for grasping the cable and aligning it with the charging coil, ultimately providing a firm grasp and perch. An open source hexacopter drone was used in this study to integrate with the charging novelty. The results provided can be used as a starting point to study the reliability of this method of charging and to further investigate perching abilities of UAVs.**

I. Introduction

There are an increasing number of UAV applications in the industrial sector. Such applications include surveying, imaging, mapping, inspecting, filming, plant and wildlife preservation, agriculture, atmospheric science monitoring, and computer vision to name a few. A major limitation that effects almost all UAVs is their operation time due to their battery life. This limits their flight time and data collecting ability and normally requires human intervention to replenish the batteries. Ideally, UAVs could harvest energy from their environment to recharge and continue operation for extended periods of time.

Toward this goal, this research presents a system allowing aerial vehicles to perch on a power line and harvest energy. Mounted on top of a UAV, Figure 1, the proposed perching mechanisms allow the UAV to hang from the power cable while also mating a U-shaped inductive coil with the powerline. The coil can then harvest energy from the AC magnetic field emitted by the powerline due to current passing through the cable. Two perching mechanisms on either side of the inductive coil provide a firm and stable grasp on the power cable. This allows the UAV to passively hang from the cable, using no energy for perching, while also gathering energy through the coil. The long-term goal is to operate equipment, such as environmental sensors, and charge onboard batteries.

This paper contributes design and evaluation of the perching and energy harvesting system, and demonstrates their application to a small multi-rotor vehicle. Analysis highlights how design variables affect inductive coil capability, which is validated via several coil prototypes highlighting balancing between magnetic permeability, weight, and size. Vehicle size and load capacity limit the size and capability of the charging system. Design and analysis of the perching mechanism is also contributed; perching mechanisms allow a wide opening to simplify alignment with the cable, while actuation causes the mechanism to pull the cable into the inductive coil and grasp it firmly. The mechanism is designed to remain closed around the cable without power applied to the actuator. Experiments evaluate performance of the resulting system.

The paper is structured as follows. Sec. II describes work related to this research and helps frame its contributions. Sec. III provides a description of the overall system and indicates specific details of the vehicle platform that constrain the

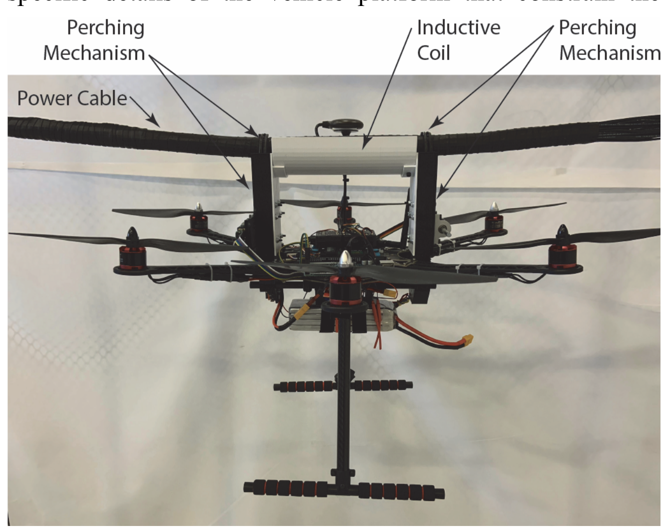

Figure 1. Perching system and inductive coil supporting a hex-a-rotor attached to a power cable.

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design of the system. Modelling and design of the energy harvesting system are provided in Sec. IV. The perching mechanism is presented in Sec V. Evaluation of the integrated system is in Sec VI, followed by Conclusions and Future work in Sec. VII.

II. Related Work

Many researchers have examined perching on flat vertical surfaces using techniques such as micro-spines [1, 2], sticky pads [3], fiber based adhesives [4, 5], spines [6], snap barbs [7], and magnets [8], many using mechanisms to create proper force closure to support wrenches and nontrivial impact velocities to trigger mechanisms, but these surfaces and perching situations are less common near power lines.

This research is more related to perching on cylindrical objects, such as branches, cables, and posts. Latching hooks have been applied for hanging from cables [9] with fixed wind vehicles. Others have used grippers, which are more practical for cylindrical objects. Pounds et al. [10] and Ghodiak et al. [11] developed underactuated compliant hand-like graspers that enable a rotorcraft to grasp and carry an object during flight. Oh [12] used an active manipulator to land on a valve. Wanchao [13] used a servo to actuate a gripper once in contact with the perch. Others have developed bird-like feet [14-16] that use passive gravitational force created by the vehicle mass to actuate legs and close grippers on the perch. None of these provide the ability to grasp a power cable and pull it into an inductive coil, nor the ability to provide a wide opening for grasping a powerline.

Methods for wirelessly charging UAVs has also been studied. Classical energy harvesting techniques capture energy from vibrations, but this is more common with large UAVs [17]. Lu et al [18] provide a review of non-EMF and EMF based techniques. Early EMF research focused on localizing relative to the powerline magnetic field and then perching on the cable [19, 20]. Muharam et al [21] examined capacitive charging. Most similar to this work is by Simic et al that examined circular coils for inductive power transfer, but that was on bench top prototypes [22]. We have been unable to find work similar to that proposed here using a u shape inductive coil placed around the cable by a manipulator. The advantage of which is high efficiency of inductive power transfer and close proximity of the coil to the conductor [18].

III. System Description

The perching system and inductive coil are designed to integrate with a target vehicle platform. Each are summarized below.

A. Hexacopter

An open-source hexacopter drone was selected as the target platform for this research due to its payload capacity and uncertainty about the mass of the perching system and inductive coil as the design process strated. The hexacopter has a 550 mm frame, a Pixhawk flight controller, GPS module, 2212 920 Kv (constant velocity) brushless motors, 10 x 4.5-inch propellers, 30-amp rating electronic speed controllers, 14.7-volt lithium polymer battery, transmitter with programmable switches, and a 10-channel receiver. The Pixhawk flight controller is able to operate the gripper via digital signals sent to an Arduino that operates the gripper as a subassembly. A switch on the remote is used to command the Arduino to open and close the perching device via the Pixhawk.

Because the lifting capacity directly affects other design decisions, a thrust evaluation was conducted. The evaluation was conducted using a motor, propeller, electronic speed controller, battery, digital scale, and an Arduino Uno microcontroller board for incremental motor output control. The motor and propeller were fixed to a digital scale, which was initialized to zero. The motor was then actuated incrementally until maximum motor output and thrust were achieved. Thrust data was collected at each increment until the maximum power output was achieved, Figure 2. Maximum thrust was reached at ~73 percent power. The horizontal blue line indicates the manufacturer's listed maximum 860g thrust for one motor, whereas results indicated a 1030 g capacity. Given six motors the maximum mass was 6.18kg, however a typical 2:1 power to weight ratio suggests 3.09 kg max, but this does not consider any other accessories. The ideal mass capacity value was used to govern design decisions for the perching device and inductive core.

B. Design Metrics

Basic design metrics guided design of the perching system and inductive coil. The system was oriented around perching on a typical powerline in a city, which was determined to be ~2.5 cm diameter in Salt Lake City. The goal was to create a system that could harvest enough energy to charge the battery or operate onboard equipment (e.g., sensing, communications, monitoring, etc) based upon typical loads in the power cable, which might vary from 100A to 1000A. Likewise, the goal was to design a perching system that could close around the power cable in 1-3 seconds to allow relatively quick attachment. The integrated system also had to remain under the ideal mass of 3.09kg.

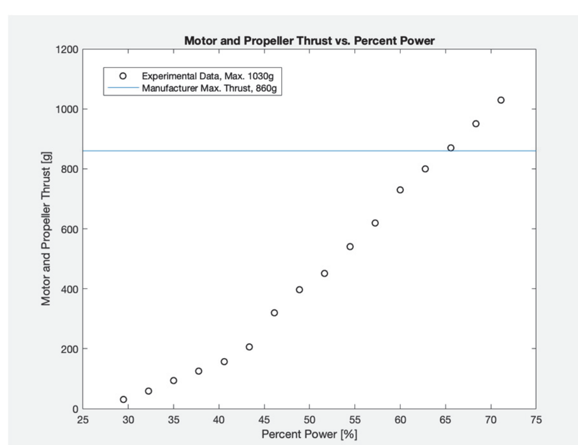

Figure 2. Motor thrust test results.

IV. Energy Harvesting

A. Modelling

The power harvesting system functions primarily on the principals of Faraday's Law of induction and Lenz's law. These principals describe the relation of a changing magnetic field and the electromotive force it generates. For this application, a powerline was used as the source of a changing magnetic field. The alternating current running through a powerline generates an alternating magnetic field that emanates from the wire. Using an inductor, this magnetic field can be utilized to generate an electromotive force that can be used to charge a drone's battery. A basic illustration of this principal is shown in Figure 3.

A model was created to analyze and design core features and dimensions related to the power output. The magnetic field strength, B_0, is first expressed as a function of the AC current, I, in the power line, magnetic permeability of the core material, μ, and distance, r:

$$B_o = \frac{\mu I}{2\pi r}$$

The change in magnetic field strength can then be determined by,

$$\frac{dB}{dt} = \omega B_0 \cos(\omega t)$$

where ω is the frequency of the magnetic field oscillation. This can then be used to estimate the voltage, V, produced by the coil wrapped around the core:

$$V = nA\frac{dB}{dt}$$

where n is the number of loops in the coil and A is the cross sectional area of a coil loop. Combining these equations, the result is:

$$V = \frac{nA\omega\mu I}{2\pi r}\cos(\omega t)$$

This highlights that the critical design variables are the number of loops, n, the permeability, μ, and the cross-sectional area, A, of the loops, where larger numbers are preferred. The most important factors considered were dimensions, magnetic permeability, and number of coils. In order to interface properly with the powerline, it was crucial to design a core that could utilize the magnetic field while also being functional with the perching mechanism.

This led to a core design featuring a u-shaped profile that the perching device could pull the powerline into. In order to maximize the loop area, the core was designed to be as long as possible. In this case, the dimension of the central body of the hexacopter combined with the propeller diameter became a limiting factor.

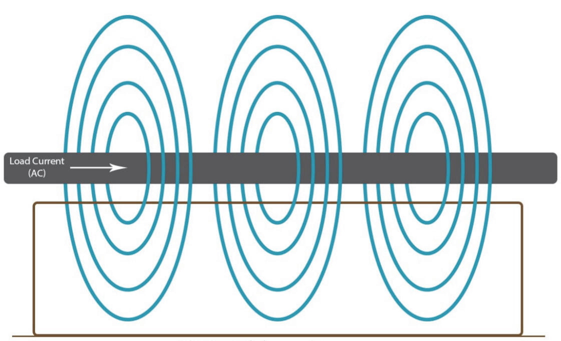

Figure 3. Energy harvesting concept.

B. Core Prototypes

With the basic dimensions of the core determined the next step was to choose a material for the core. This was an important decision due to the importance of the material property of magnetic permeability and the effect it has on induction. Simply put, a higher magnetic permeability translates into a higher power output from the inductor. Three materials were tested to determine what would best meet the power harvesting needs of for this project. Prototyping started with iron infused PLA (middle picture, Figure 4) a 3D printing material, which was light and made rapid prototyping of the inductive core easy. However, this material had a fairly low permeability and was not suitable as the response from testing was not high enough to produce meaningful power.

To validate the importance of shape and permeability, a short section of black iron tubing (left picture, Figure 4) was used. This showed promising results during testing, but would have been hard to work with to make a core with the desired dimensions. This core was still useful because it was used to help validate the MATLAB code used to model how different parameters would affect the overall effectiveness of the power harvesting capabilities of the inductor.

Given the limited capability of the other prototypes, it became clear that a high permeability material was required. While laminated ferrite plates stacked to make the u channel would have been ideal for reducing eddy current, budget and manufacturing limitations were limiting factors. The selected core repurposed ferrite noise suppressors (right picture, Figure 4). The ferrite suppressors have a fairly high magnetic permeability and were also pre-formed in a U shape ideally suited to the perching system. A summary of the prototype properties and their responses are shown in Table 1. As the results indicate, there are tremendous advantages to using ferrite for the core material even though the material adds a significant amount of weight to the drone.

After choosing a material the final construction of the core was undertaken. Two noise suppressors were dismantled and then epoxied together to form the long u-shaped core. Two posts were then 3D printed and epoxied to the tops of the u-shape to extend the u and aid in winding copper wire around

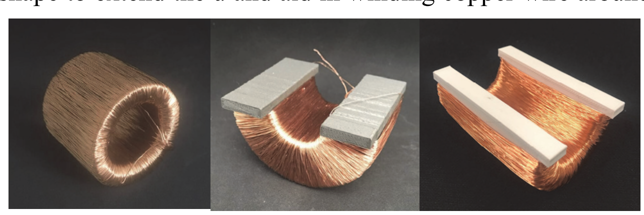

Figure 4. Core concepts.

Table 1. Core prototype specifications.

Material	Loop Area (cm^2)	Estimated Relative Permeability	Number of Coils	Load Current (A)	Vrms Response (V)
Iron-PLA	10.32	1.7	~850	92	0.187
Black Iron	3.15	10	~120	52	0.076
Ferrite (Mn-Zn)	13.68	30	~1800	92	4.46

the core to make the coils. The inductor was then hand wound with copper wire and although the final number of coils is not precisely known it was estimated to be close to 1800 loops. The completed inductor was then tested to determine its actual power output capabilities.

V. PERCHING MECHANISM

A. Mechanism Design Goals

The perching device was designed to allow the drone to connect to and hang from a power cable while positioning the inductive recharging device at an acceptable distance from the power cable. The device's physical components had to work with the drones existing frame, as well as be minimally invasive to the drone's electronic components. Metrics considered were the total weight of the drone with the recharging core and perching device, as well as the closing and opening speed of the device. Upon researching the design of the inductive core, it was determined that the maximum power draw from the cable would occur the deeper the cable was pulled into the u-shape of the core. Considerations also had to be made for the wind and weather of outside environments while perching in order to create a device that would grasp the cable without the drone being in the perfect position. The perching device electronics would also have to integrate with the onboard electronics of the drone.

B. Mechanism Concepts

Early design considerations were quite different from the final design. Originally, a primary concern was the inductive core would be quite heavy, so options were explored where the perching device and the core would be located below the drone for improved stability. It was realized however, that in order to maintain balance on top of a wire, the drone would need to use more energy than if it were in a resting state, hanging below the wire. It was specifically for this purpose that the core was and perching mechanism were placed above the body of the drone. Some mechanisms that were considered included similar hook designs with different ways of actuating the hooks. One design consideration was simply creating the inductive core into the shape of a hook. This design was passed over due to the concern of difficulty placing the hook on the power line and the overall height of core device. With a basic idea of mounting location other design criteria thought out, the final design was conceptualized.

C. Perching Mechanism Design

The final perching mechanism design, Figure 5, utilizes a rack and pinion gear system to linearly actuate dual hooks and maneuver the power line into position over the inductive core. When the hooks are open, Figure 6 (left), they allow a wide opening to maneuver the drone into position under the wire.

The device uses an electric motor to drive the pinion of a rack and pinion gear system. The dual hooks are attached to the rack portion of the gear system. As the gear rack is driven downward by the motor it forces the hooks to contact a housing which forces the hooks to close around the wire, Figure 6 (center). As the arms move down, they contact the wire and move it into position above the core. The device continues to move the hooks downward after the hooks fully enclose the wire pulling the wire farther into the u-shape of the core. As the wire reaches its desired position, Figure 6 (right), the bottom of the gear rack contacts a limit switch which stops the movement of the motor.

Torque and force calculations were performed to find the overall torque required to lift the drone, Figure 5 (left). It is assumed that a force F is applied to each rack to support half the vehicle mass, m,

$$F = \frac{m}{2} g = \frac{(2.251kg)}{2}\left(9.81\frac{m}{s^2}\right) = 11.04N$$

which is supported by the pinion gear, with pitch radius r, resulting in the gear torque,

$$T = rF = (.011m)(11.04N) = 0.12\ Nm$$

Pololu Micro Metal Gearmotors (1000:1 MP 6V) with 1000:1 reduction were identified since they provided a safety factor of 2.65 at maximum motor power and safety factor of 2.11 relative to the rated instantaneous torque of the gearbox.

Detent torque and holding torque of the motor was also a selection criterion as the weight of the drone would be hanging from the device when it was not powered. The motor torque, is then

$$T_{Mot} = \frac{T}{n} = \frac{0.12Nm}{1000} = 0.00012\ Nm$$

based upon a gear box ratio of $n = 1000$. Estimates were that this was a sufficiently small torque that friction in the motor and gearbox would be sufficient to hold the gripper in position when motor power was removed. This is verified in the experimental evaluations later.

Closing time calculations were performed to make sure the motor could perform the movement in a reasonable amount of time. The no-load speed of the gear motor is rated as 22 rpm,

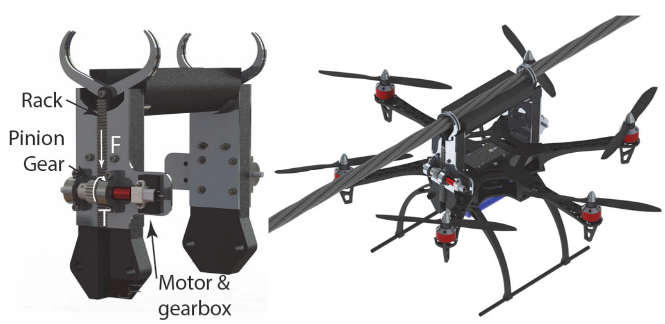

Figure 5. Final perching device (left) and mounted on drone (right).

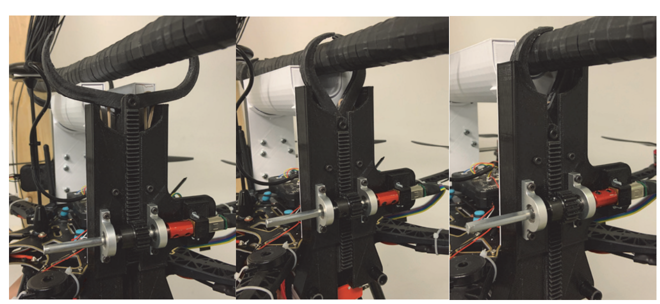
Figure 6. Perching device closing around power cable.

thus the rack speed, V_{rack} is,

$$V_{Rack} = 2\pi r\omega =$$
$$= (2\pi)(11mm)(22\ rpm)\left(\frac{1\ min}{60\ sec}\right)$$
$$= 25\frac{mm}{sec}.$$

The stroke of the rack is 57mm, thus, the closing time is 2.28 seconds, which was deemed reasonable for actuating the gripper. Thus, the motor was also selected for its ability to support the vehicle and actuate the gripper relatively quickly. The motor was also compact and lightweight, making it ideal.

Total mass capacity was considered when selecting material for the perching device. A decision to use 3D printed parts would be the best choice for material. FEA testing was used to analyze the critical components subject to loads. Concerns about the bending forces imposed on the motor shaft emerged as the design progressed. A pillow block bearing system, Figure 6, was developed to minimize bending forces on the motor shaft. This design ensures the shaft of the micro motor is only exposed to torques.

D. *Integration*

The final design step was incorporating the inductive core into the perching device. A housing was created around the core which then mounts to the perching device. This component also acts as a structural member, providing support between the two perching mechanisms at either end of the core. The perching device was then mounted on support bars across the bottom of the drone. The Pixhawk flight controller was then used to send a digital signal to an Arduino controlling the perching mechanism. An Arduino and motor driver were used to control the actuation of the perching device. An encoder was used to sense perching device position. A limit switch determined when the mechanism was closed and allowed initialization of the encoders.

E. *Perching Mechanism Evaluations*

Several tests were performed to ensure the perching device would perform its function as intended. A static test was performed to ensure the mechanism was working as intended. This involved opening and closing the device 5 times. The device was successfully able to perform the test.

A test was performed to test the apparatus ability to grab the wire by holding the drone up to the test apparatus and closing the claws around the cable. The drone was able to grasp the cable and pull it down into the core successfully.

A hanging test was performed where the perching device was fully closed around the cable and the weight of the drone and inductive core was hanging from the closed device. The perching device was able to support the weight of the drone both with the motors powered and without the motors powered.

VI. Experimental Results

A. *Apparatus*

A test apparatus, Figure 7, for analyzing the functionality of the energy harvesting inductive core was required as prototyping progressed. Legal restrictions as well as safety were major concerns in using high voltage power lines. The primary requirements were to access a 100-1000 Amp current on a one-inch diameter cable without creating a safety issue, both during early testing and with an audience. Options were explored that would allow appropriate testing of the inductive core using a standard 120 V power supply as opposed to a high voltage source.

To simulate the various amperages required, a test apparatus was designed using 14-gauge coated wire. The wire was coiled together sixty-one times into a single roll of wiring which was then wrapped in rubber splicing tape. A micrometer was used to confirm that the outside diameter of the rolled wire coil would fit into the 2.5 cm (~one-inch) wide inductive core.

To support the cable, a wood frame was constructed, and carabiners were used to secure it in place. The support frame width allowed for the drone to hang from the center of the cable without interference. Each end of the wire was fastened to a male and female 120 V plug to allow for source and load connections respectively.

The testing apparatus functioned by plugging into a standard outlet and having a load draw on the other end of the wire. The roll of wires paired together simulated a large cable with current draw through the one-inch area within the core, creating the magnetic field necessary for inductive charging. Various loads were applied using a space heater and a heat gun with a fan controller to enable variation of the power draw and ultimately full control of the current through the test apparatus.

B. *Energy Harvesting*

After the final prototype was constructed, a testing apparatus was constructed and used to test the full power harvesting capabilities of the completed core. The load current was measured by using a clamp meter to measure the current in the single wire which was then multiplied by 61, the number of times the wire was looped. This reading was verified by using a clamp meter to measure the current in the wire bundle. This method was used because the clamp meter used to measure the simulated current could only reliably measure current up to 400 amps.

Figure 7. Perching test apparatus.

The inductive coil was then connected to a 6-ohm load resistor and then placed around the 1-inch thick test apparatus wire bundle. Using a voltmeter, the voltage drop across the resistor was then measured at various load currents from 100 to 1000 A in increments of 100 A. Using the measured voltage drop and the resistance value of the load resistor, the power output was calculated. Figure 8 is a graphical representation of the power output of the inductive coil at each of the tested load currents. Current in a powerline is variable depending on the loads the powerline is supplying.

Assuming the average current in a given powerline to be close to 800 A, and with the current power harvesting capabilities it would take over 3 days to completely recharge the drone. It would provide sufficient power for extended low power operations. This is lower than desired. There are several options for improving charging capability. Since the drone is currently is below the mass additional semi-cylindrical coil segments could be added to take advantage of the complete field around the section of power cable being grasped. The current U shaped coil does not capture any of the energy from the EMF field above the gripper.

Another possibility for improving the coil would be to fabricate the charging coil from ferrite plates as mentioned in Sec IV.B. Ferrite plates limit the formation of eddy currents inside of the core, which allows more of the EMF energy to be transmitted to the windings, instead of wasteful currents and heat generation inside the coil.

Finally, only a simple load resistor was used for converting the induced coil voltage into energy. The load resistor certainly could have been optimized, as a minimum, to maximize energy dissipation. Likewise, circuitry optimized for capturing energy and boosting the voltage to usable levels for applications such as charging or operating onboard circuitry should be considered.

C. Perching Mechanism

The results of the testing proved that the mechanism was able to support the weight of the drone, Figure 9 and Figure 10. The drone was able to hang from the testing apparatus without being powered by the onboard battery meaning the detent torque of the motor and overall friction of the device exceeded the .00012 Nm torque which was being applied to the motor while the drone was hanging.

The perching device also was able to actuate its full motion in an acceptable amount of time. The time measured for the device to go from fully open to fully closed was approximately 2.5 seconds. This was slightly longer than the theoretical closing time however was still within reason. The biggest reason for the difference is that the calculations shown in Sec V.C were based upon no load torque with the intention that friction in the mechanism would be sufficiently small to have minimal effect on the mechanism response. The voltage applied to the motors was only 6 V, however, so improved response could be achieved by simply increasing that voltage.

D. Integrated System

After all the individual components were tested flight tests were performed to determine the drone's ability to fly with the weight of the added systems. Flight test were performed in a controlled flight volume. The drone successfully completed a one-minute flight with the perching device and inductive core mounted on the drone. The drone was also tested with a maintain altitude mode engaged and roll/pitch inputs applied to the system to observe dynamic response. Ardupilot control roll/pitch sensitivity gains were first tuned for the hexarotor without the gripper attached, resulting in a sensitivity of 0.15. The vehicle was then manually flown manually and confirmed to respond well to roll/pitch commands. The perching mechanism and coil were then

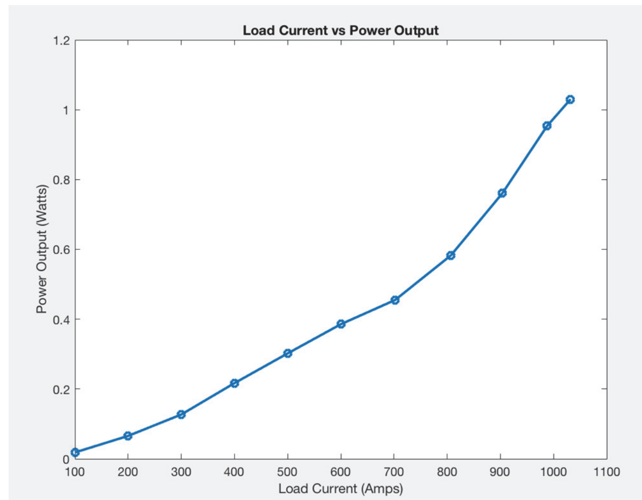

Figure 8. Energy harvesting load current vs. power output.

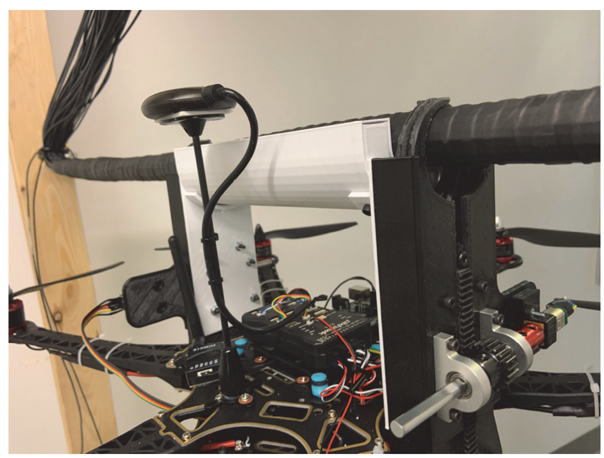
Figure 9. Perching device attaching to apparatus.

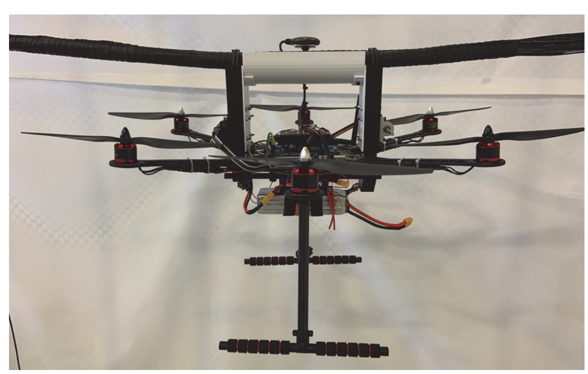
Figure 10. Drone hanging from test apparatus.

attached to the system and similar tests were repeated. The system had difficulty flying with the previous sensitivity level, so the sensitivity was retuned with the gripper attached for a sensitivity of 0.20 and then 0.25 in order to provide similar flight capability, although the vehicle was clearly working harder to support the additional work. As expected, the system become more sensitive to battery charge level with the added weight. Perching was also demonstrated using manual control. Figure 11 to Figure 13 show the fully assembled drone during flight and perching tests. Future work should focus on flight control techniques, such as visual servoing, to help the UAV align and grip the perch.

Figure 11. Fully assembled drone during flight test.

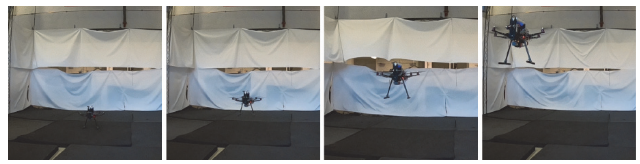

Figure 12. Image sequence at 3 sec intervals from flight test.

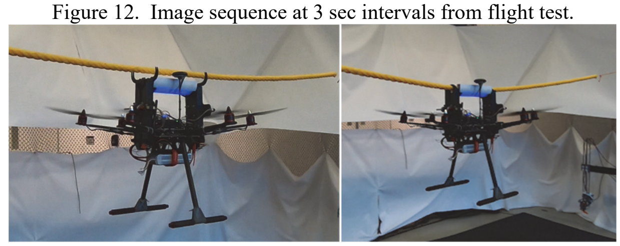

Figure 13. Perching during flight.

VII. Conclusions and Future Work

Inductively recharging a UAV using powerlines is a promising technology for use in commercial and industrial applications. This study explored various options for both the perching mechanism and inductive core which resulted in a successful attachment to the power cable as well energy harvesting from the cable. With some improvements, this basic proof-of-concept could be tailored to meet the specific needs of the UAV in its specific application. Future work should emphasize improved energy harvesting capabilities. Specific changes may include but are not limited to core shape redesign to facilitate increased charging capability (may include changes to core material and shape of the inductor), flight assistance to aid in perching, fully autonomous flight planning and an integrated application.

References

[1] A. Lussier Desbiens, A. T. Asbeck, and M. R. Cutkosky, "Landing, perching and taking off from vertical surfaces,", *Int J Rob Res,* Conference Paper vol. 30, no. 3, pp. 355-370, 2011, doi: 10.1177/0278364910393286.

[2] J. Thomas *et al.*, "Aggressive flight with quadrotors for perching on inclined surfaces,", *Journal of Mechanisms and Robotics,* Article vol. 8, no. 5, 2016, Art no. 051007, doi: 10.1115/1.4032250.

[3] M. L. Anderson *et al.*, "The sticky-pad plane and other innovative concepts for perching uavs," in *47 th AIAA Aerospace Sciences Meeting*, 2009.

[4] L. Daler, A. Klaptocz, A. Briod, M. Sitti, and D. Floreano, "A perching mechanism for flying robots using a fibre-based adhesive," in *2013 IEEE Int Conf Robotics and Autom*, Karlsruhe, Germany, May 6-10 2013: pp. 4433-4438, doi: 10.1109/ICRA.2013.6631206.

[5] J. Hao *et al.*, "Modeling the dynamics of perching with opposed-grip mechanisms," in *2014 IEEE Int Conf Rob and Autom (ICRA), 31 May-7 June 2014*, pp. 3102-8, doi: 10.1109/ICRA.2014.6907305.

[6] D. Mellinger, M. Shomin, and V. Kumar, "Control of quadrotors for robust perching and landing," in *Int Powered Lift Conf 2010*, Philadelphia, PA, 2010, pp. 119-126.

[7] M. Kovač, J. Germann, C. Hürzeler, R. Y. Siegwart, and D. Floreano, "A perching mechanism for micro aerial vehicles," *J Micro-Nano Mechatronics,* vol. 5, no. 3-4, pp. 77-91, 2009, doi: 10.1007/s12213-010-0026-1.

[8] P. Chirarattananon, K. Y. Ma, and R. J. Wood, "Fly on the wall [robotic insects]," in *2014 5th IEEE RAS & EMBS International Conference on Biomedical Robotics and Biomechatronics (BioRob), 12-15 Aug. 2014*.

[9] R. Cory and R. Tedrake, "Experiments in fixed-wing UAV perching," in *AIAA Guidance, Navigation, and Control Conf*, Honolulu, HI, 2008: AIAA, pp. 1-12.

[10] P. E. Pounds, D. R. Bersak, and A. M. Dollar, "Stability of small-scale UAV helicopters and quadrotors with added payload mass under PID control," *Autonomous Robots,* vol. 33, no. 1-2, pp. 129-142, 2012, doi: 10.1007/s10514-012-9280-5.

[11] V. Ghadiok, J. Goldin, and W. Ren, "On the design and development of attitude stabilization, vision-based navigation, and aerial gripping for a low-cost quadrotor," *Autonomous Robots,* vol. 33, no. 1-2, pp. 41-68, 2012, doi: 10.1007/s10514-012-9286-z.

[12] C. Korpela, M. Orsag, and P. Oh, "Towards valve turning using a dual-arm aerial manipulator," in *2014 IEEE/RSJ Int Conf Intel Rob and Sys (IROS 2014), 14-18 Sept. 2014*, pp. 3411-16, doi: 10.1109/IROS.2014.6943037.

[13] C. Wanchao, K. H. Low, K. H. Hoon, and J. Tang, "An optimized perching mechanism for autonomous perching with a quadrotor," in *2014 IEEE Int Conf Rob and Autom (ICRA), 31 May-7 June 2014*, pp. 3109-15, doi: 10.1109/ICRA.2014.6907306.

[14] M. L. Burroughs, K. Beauwen Freckleton, J. J. Abbott, and M. A. Minor, "A Sarrus-Based Passive Mechanism for Rotorcraft Perching," *J of Mech and Rob,* vol. 8, no. 1, doi: 10.1115/1.4030672.

[15] P. Xie, O. Ma, L. Zhang, and Z. Zhao, "A bio-inspired UAV leg-foot mechanism for landing, grasping and perching tasks," in *AIAA Atmos Flight Mech Conf, 2015*, 2015, doi: 10.2514/6.2015-1689.

[16] M. Tieu *et al.*, "Demonstrations of bio-inspired perching landing gear for UAVs," in *Proc SPIE*, 2016, vol. 9797, doi: 10.1117/12.2218167.

[17] A. Erturk, J. M. Renno, and D. J. Inman, "Modeling of piezoelectric energy harvesting from an L-shaped beam-mass structure with an application to UAVs," *J Intell Mater Syst Struct,* Article vol. 20, no. 5, pp. 529-544, 2009, doi: 10.1177/1045389X08098096.

[18] M. Lu, M. Bagheri, A. P. James, and T. Phung, "Wireless charging techniques for UAVs: A review, reconceptualization, and extension," *IEEE Access,* vol. 6, pp. 29865-29884, 2018.

[19] J. Moore and R. Tedrake, "Powerline perching with a fixed-wing UAV," in *AIAA Infotech@ Aerospace Conference and AIAA Unmanned... Unlimited Conference*, 2009, p. 1959.

[20] J. Moore and R. Tedrake, "Magnetic localization for perching UAVs on powerlines," in *2011 IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2011: IEEE, pp. 2700-2707.

[21] A. Muharam, T. M. Mostafa, and R. Hattori, "Design of power receiving side in wireless charging system for UAV application," in *2017 Int Conf Sust Energy Eng and Appl (ICSEEA)*, 23-24 Oct. 2017 2017, pp. 133-139, doi: 10.1109/ICSEEA.2017.8267698.

[22] M. Simic, C. Bil, and V. Vojisavljevic, "Investigation in wireless power transmission for UAV charging," *Proc Comp Sci,* vol. 60, pp. 1846-1855, 2015.