NASA/TM–20240010588

ENLIGHTEN: Electrical Network Line Inspection Guided by High-Speed Technology & Electromagnetic Navigation

** All authors contributed equally to this memo. The names are listed alphabetically by first name.*

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August 2024

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National Aeronautics and
Space Administration

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Mountain View, CA

August 2024

Acknowledgments

The NASA OSTEM Internship Program and Shannon Zelinski from the NASA Ames Research Center made this technical memorandum possible. The authors would also like to thank their team mentors, Haroon Khan and Alexey Munishkin, for their guidance throughout the 8-week duration of the internship.

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I. Abstract

Natural disasters are a major cause of power outages, primarily due to their damage to power line infrastructure. As a result, the current state of power maintenance, with a heavy reliance on manual labor, is in trouble. Its lack of speed and autonomy must be addressed to ensure power security for households and institutions worldwide. This innovative approach explores how High-Speed Unmanned Aerial Vehicle (HSUAV) technology can inspect power line infrastructure rapidly in response to natural disaster scenarios. The HSUAV technology will be accompanied by enhanced sensory equipment including light detection and ranging (LiDAR), thermal imaging, and electromagnetic field (EMF) navigation. It would also be supplemented by innovative forms of machine learning models and recharging systems to efficiently detect anomalies in power line infrastructure. The proposed system, ENLIGHTEN, can help restore power in affected communities after a devastating natural disaster, greatly improving relief efforts. In the future, ENLIGHTEN can be expanded beyond the United States and shared worldwide, effectively mitigating the consequences on a larger scale.

II. Problem and Solution Statement

Multitudes of natural disasters affect the entire globe, having caused 83% of power outages in the past two decades [1]. A primary cause of these outages is the poor management of power utilities, often leading to inefficient disaster relief and expensive consequences, with cost averages ranging from $18 billion to $33 billion per year [2]. Moreover, in 2022, U.S. electricity customers experienced an average of five and a half hours of electricity interruptions [3]. These issues call for an application that can effectively mitigate these consequences.

In response to the inefficient management of power lines and inadequate disaster management, the following research proposes a framework that effectively uses HSUAVs for power line inspection, maintenance, and relief. The HSUAVs would be used to survey vulnerable areas, observe these areas in disasters, identify damaged power lines, and alert authorities to repair damaged power lines.

III. Introduction

A. Context

The rise of climate change has created a pressing concern in response to natural disasters and extreme weather. Every 1-degree Celsius increase from global warming causes a 7% higher amount of water vapor to evaporate into Earth's atmosphere, fueling the development of more powerful storms [4]. The rapid frequency of disasters, like winter storms, hurricanes, and wildfires, adversely influences utilities and power lines and affects millions worldwide.

Much of U.S. energy infrastructure dates to the 20th century with the invention of revolutionary generation tactics and the establishment of the energy grid. Consequently, most transmission and distribution lines for power were constructed in the 1950s and 1960s with a 50-year life expectancy [5]. The aging layout leads to sagging, exposed lines, and the potential to overheat and malfunction, which increases the risk of wildfires. For example, in February 2024, the Smokehouse Creek Fire in Texas, the largest wildfire in the state's history, burned over a million acres of land. The cause was an old power line from a local utility company [6]. Poor management of electrical infrastructure has led to two of the largest wildfires in both Texas and California. Each year, insufficient planning and infrastructure of these utilities cost the country billions of dollars, which could have been avoided.

Across the United States, disasters lay waste on cities and their utilities. For example, in September 2022, Hurricane Ian formed near the coast of Africa and developed into a category-five hurricane before later devastating Florida. As a result, 4.4 million customers in the U.S. lost power, making it the costliest hurricane in Florida's history [7]. In late August of 2018, Hurricane Harvey dumped almost 62 inches of rain over areas of Texas and caused over 1.67 million people to lose power in the state due to the severe flooding [8].

Natural disasters affect more than just the U.S.; their unpredictable nature has caused devastating damages worldwide in terms of casualties, the economy, and the environment. Currently, power lines also frequently experience interruptions due to falling limbs, deferred maintenance, and neglected infrastructure. Considering this, implementing ENLIGHTEN would help the U.S. to be better equipped for maintenance as well as to avoid the drastic consequences of extreme weather events and natural disasters.

B. Past Research

Research developments at the intersection of drone technology and power line systems are relatively new. In the European Union, researchers have developed a framework that uses artificial intelligence (AI) and aerial robots to inspect and maintain power line systems. This system, named AERIAL-CORE, is said to be the "first autonomous system that combines various innovative aerial robots." AERIAL-CORE involves the use of Vertical Take-Off and Landing (VTOL) drones that have the capabilities of Red Green and Blue (RGB) color- and event-based tracking for power lines. In addition, the system has considered the safety of humans in construction areas — using 3D LiDAR technology for detecting potential obstacles, RGB cameras for monitoring workers, and global positioning system (GPS) technology for the movements of the HSUAVs themselves [9].

Tables 1 and 2 below present other forms of previous research in these fields.

Table 1: Different Aspects of Current Research about Inspection with Unmanned Aerial Vehicles (UAVs).

Past Research	Technology Used	Applications	Use of UAVs
Unmanned Aerial Vehicles for Power Line Inspection: A Cooperative Way in Platforms and Communications [10]:	• UAV images • Epipolar images • Block bundle adjustment software	• General power line inspection.	• Generating images • Surveillance
Mitigating avian collision with power lines: a proof of concept for installation of line markers via unmanned aerial vehicle [11]:	• Satellite • Wireless communication	• Transmit videos and images of power lines during inspections	• Generating footage and images • Substitutes human labor
Automatic Power Line Inspection Using UAV Images [12]:	• LiDAR sensors • Infrared cameras • Ultraviolet cameras • Optical cameras	• General power line inspection	• Surveillance • Substituting human labor

Table 2: Different Research Papers' Methods of Repairing Power Lines.

Past Research	Repairing power lines after disasters
Power System Resilience under Natural Disasters [13]:	Created a scheduling system for multiple crews for repairs.
Creating a List of Works on Reconstruction of Infrastructure Elements in Natural Disasters Based on Information Technologies [14]:	Checking which power lines need to be repaired urgently to find out where to send a repair team.
Reducing the Vulnerability of Electric Power Infrastructure against Natural Disasters by Promoting Distributed Generation [15]:	Designed distribution generation technology that increases the reliability of a power grid after a disaster.

IV. Approach

A. HSUAV Specifications

1. Powertrain

ENLIGHTEN's powertrain is essential to achieving the goal of maximum speed response in natural disaster scenarios. This section will discuss considerations when choosing the components that provide the UAV with its highest potential speed. One of the most crucial parts of the powertrain is providing the motors with the maximum voltage to reach peak speeds. For this reason, an extremely high-voltage LiPo battery with many cells in parallel is the best option. The wire gauge used to route power to the Power Distribution Board, Electronic Speed Controllers (ESCs), and motors would also need to be able to handle the thousands of potential watts of power going between the components [16].

1.1 Motors [16-19]:

When choosing the best motors for a high-speed UAV, the constant velocity (Kv) rating, required rotational force (torque), volume, and magnet size should be considered. A motor with a larger stator volume and permanent magnet size produces higher available torques [18]. However, these aspects shouldn't compromise the weight of the motor, which could hinder the performance of the UAV more than the extra size would improve the total power output. For more information regarding UAV motors, refer to [16]-[19]. Considering these aspects, a large volume and relatively high Kv motor specification would be a 3115 1500Kv brushless direct current (BLDC) electric motor [16].

1.2 Propellers [20-23]

When choosing the right propeller to maximize speed and maneuverability, three main traits must be considered: the propeller diameter, traveling distance per revolution of a propeller (propeller pitch) and number of blades [20]. These aspects influence the torque required to spin the propellers, the thrust produced, efficiency, and the overall speed. The relationship between these characteristics of propellers is shown in Table 3. For more information regarding UAV propellers, refer to [20]-[23]. Based on an earlier high-speed multi-rotor UAV project, an efficient propeller would have a 7” diameter and an 11” pitch [16].

Table 3: Relationships Between Propeller Characteristics.

Propeller Characteristic	*Torque Required (T)*	*Thrust Produced (N)*	*Efficiency (E)*	*Responsiveness (R)*	*Propeller Speed (S)*
Diameter (D)	**D↑ T↑**	**D↑ N↑**	**D↑ E↑**	**D↑ R↓**	—
Pitch (P)	**P↑ T↑**	**P↑ N↑**	—	—	**P↑ S↓**
Blade Number (B)	**B↑ T↑**	**B↑ N↑**	**B↑ E↓**	—	—

2. Frame Design

The ideal frame design of a high-speed UAV should maintain a compact and stable shape that can store various sensors, such as GPS, LiDAR, infrared, and EMF, while minimizing drag.

ENLIGHTEN plans to implement a quadcopter design to ensure UAV and motor stability. A few advantages of this design are as follows:

1. The propellers of a quadcopter can generate lift by rotating in opposite directions. Having two rotors spinning clockwise and two rotors spinning counterclockwise generates a balance in forces, increasing general stability [24].
2. Quadcopter designs can be operated and maneuvered efficiently while airborne, with easy vertical takeoff and landing procedures [24].

In addition to a quadcopter design, another consideration would be the frame's shape. ENLIGHTEN proposes using a custom X-shaped frame design (see Figure 1) to ensure UAV stability while providing ample space to install sensors vertically. Furthermore, an X-Frame design offers an aerodynamic structure to optimize agility [25].

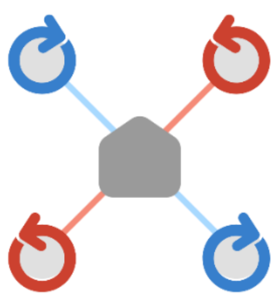

Figure 1: An X-Frame quadcopter UAV design. The rotors, which will be used for the propellors, are represented by the blue and red arrows.

Above the frame, a sturdy nose cone design (see Figure 2) must be implemented to maximize aerodynamic balance and forward flight optimization in the UAV. The cone-shaped design would contain sensors, including EMF, GPS, LiDAR, and infrared thermal sensors (see section 3). Moreover, it is necessary to consider the orientation of the sensors themselves.

The UAV must account for a vertical GPS sensor because of the horizontal flight path used to inspect power lines. In addition, LiDAR and thermal sensors must either be outside the cone or exposed through a window in the cone. This is because LiDAR sensors collect data using light from the atmosphere, and thermal sensors inspect heat and temperature changes from the atmosphere as well. There are several window materials that can absorb these waves, including germanium and calcium fluoride.

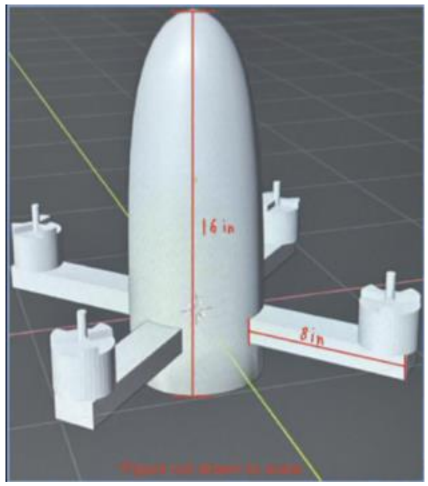

Figure 2: X-Frame and Cone 3D Design for ENLIGHTEN.

3. Sensors

Drones equipped with various sensors assist in power line fault detection. These include a Thermal Camera, GPS, EMF sensor, and LiDAR. For more information on how these sensors will be used to detect power line anomalies, see section B3.

3.1 Thermal Camera

Infrared, or thermal sensors, detect heat signatures in geographic areas by mapping out hot and cold spots. Thermal radiation travels through an image processor to produce a thermal image, which can be used along a power line to detect heat anomalies and potential faults [26].

3.2 GPS

The Global Positioning System is a navigation system that uses satellites in orbit from the United States Department of Defense (DOD). The GPS receiver must use three satellites to calculate a two-dimensional position. If the GPS receiver uses four or more satellites, a user's three-dimensional position can be determined, including the longitudinal axis, lateral axis, and height [27].

3.3 LiDAR

All drones are equipped with a light detection and ranging sensor, also known as LiDAR. It is a remote sensing tool that uses laser light to measure distances and create a 3D terrain map. A laser sends a light pulse to a target and bounces back to the sensor's receiver. The time-lapse is then recorded between the light pulse and the reflected, scattered light pulse to collect 3D data on the drone’s surroundings [28]. Compared to high-resolution cameras, the LiDAR sensors can collect 3D geographic data. The ability to collect this data allows the drone to navigate obstacles and collect large-scale, real-time, geographic data for human counterparts to decipher and analyze. The LiDAR sensors are used with other tools like power line recharging and digital twin modeling systems. As an integral part of the UAV system, LiDAR sensors provide highly accurate and valuable data surrounding energy infrastructure that can be modeled into real-time digital twins, allowing engineers to test and monitor operations sustainably.

3.4 Raspberry Pi

An onboard processing unit would be required to take inputs from the sensors and process their data to help with navigation and power line fault detection. This autonomous decision system would use a Raspberry Pi onboard the drone to minimize the need to send data to the cloud or to another server, which could cause unnecessary latency in detection and decision-making [29].

3.5 EMF

The EMF-828 is an example of a reliable EMF radiation tester that can determine EMF levels around power lines [30]. UAVs with this can sense electromagnetic interference (EMI) and set a minimum approach distance using Minimum Approach Distance (MAD). Tri-axis meters measure three axes simultaneously to obtain more accurate data [30]. For more information, see Section B1 in Autonomous Operations.

4. Stability and Control Testing

For the control testing, a digital twin model of ENLIGHTEN would be used to test the aerodynamics and stability of its frame. Along with digital twin modeling, wind tunnel/testbed tests would be used to evaluate the aerodynamics and drag forces of the drone, as well as motor power and efficiency, once it has been prototyped. Then, these designs will be compared to the initial digital twin model to assess the building process's accuracy and confirm the component research results. Additionally, proportional-integral-derivative (PID) tuning can be utilized to achieve the most efficient speed and control characteristics [16].

4.1 Digital Simulation

There are a multitude of computational fluid dynamics (CFD) simulation software that can be used to simulate the digital twin multirotor UAV and improve its aerodynamic performance before producing a prototype. One of these is NASA's OVERFLOW high-fidelity CFD software [31]. OVERFLOW was found to be equivalent to other NASA CFD software such as FUN3D and CFL3D [32]. This software has been specifically used to analyze multi-rotor UAV performance previously at NASA Ames [33] (see Figure 3). In this previous work, the authors gained many insights into the fault points and advantages of certain aspects of the commercial UAVs tested [34].

Another CFD software that would be useful in refining the propeller and motor is RotCFD [35]; this CFD software has been specifically designed for rotor simulation and user experience. NASA's Multirotor Test Bed (MTB) [36] has confirmed its accuracy. Using both RotCFD and OVERFLOW, the powertrain's specifications and the frame's aerodynamic design can be effectively analyzed to ensure that the drone can achieve the maximum speeds possible.

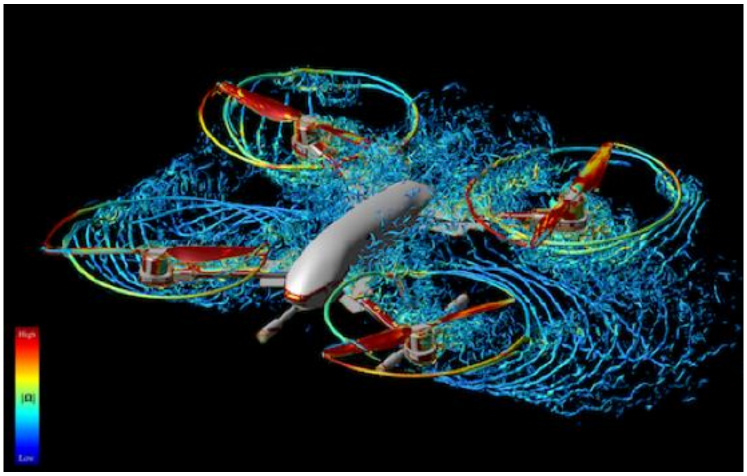

Figure 3: OVERFLOW CFD Simulation [33].

4.2 Wind Tunnel Testing

Ames Research Center's Multirotor Test Bed (MTB) can test the motor and propeller configurations to find the most structured version for maximum thrust and efficiency. Each motor/propeller position can be configured on the MTB, and the individual thrust of each motor in all six axes can be recorded to find the best high-speed configuration. The Ames wind tunnel can also be used to ensure that the HSUAV's frame can stand up to the higher wind speeds that might be faced in a quick response disaster recovery application [36].

4.3 Control Algorithms

Precise control is essential to prevent malfunctions when dealing with a very high-speed UAV system. A proper control algorithm must be chosen to achieve such precise speed and rotational control. PID control is the most common algorithm used in the commercial and hobby quadcopter industries [37]. Another control algorithm that has been researched for quadcopter use is the Linear Quadratic Regulator. This control algorithm works well in following a set path even with wind and other disturbances. However, when avoiding potential obstacles it struggles to regain its previous path [38]. Table 4 below compares some control algorithms. Due to the widespread use of PID and its flexibility with tunable parameters, it would be the best control system for the multirotor UAV.

PID controllers have a simple framework and have been used to control UAVs in real-time and assist in navigation structures [39]. The goal of using a PID controller is maintaining a negative feedback loop. An example of a negative feedback loop is maintaining equilibrium with temperature in a room. When the temperature rises too high, the air conditioning is turned on to cool it down. On the other hand, when the temperature decreases beyond a certain point, the thermostat is turned up to maintain a normal room temperature. In the context of ENLIGHTEN, a PID controller maintains a negative feedback loop so that no change in drone behavior occurs. Furthermore, PID controllers are known to be the most precise and secure controllers. ENLIGHTEN will use the controller to balance temperature, flow, speed, and pressure [40].

Table 4: Control Algorithms Comparison.

Algorithms	*Advantages*	*Disadvantages*
PID	• Most common • Easy to tune to application	• Cannot adapt to changes in UAV characteristics
Linear Quadratic Regulator	• Good path following	• Cannot avoid obstacles • Not very common
Backstepping Control	• Less computationally intensive • Handles disturbances well	• Not very reliable • Not very common
Adaptive Control Algorithms	• Adapts to changes in UAV characteristics	• Hard to tune • Not very common • Require external feedback

B. Autonomous Operations

1. EMF Sensor Navigation

1.1 Basic System

EMF sensors in ENLIGHTEN serve two purposes. They can help avoid the effects of EMI and guide the multi-rotor UAV along power lines for inspections. These tasks are enabled by two features: a Minimum Approach Distance (MAD) and a containment boundary [41] (see Figure 4). The MAD is represented by the red arc in the image, which is a distance threshold set by the user to prevent collisions and EMI. The containment boundary (green line in the image) is defined by the autonomous decision system, which takes data from the EMF sensor and gives instructions to the onboard flight controller to maintain course over the powerlines [41]. This active adjustment allows for adaptation to different levels of powerline infrastructure.

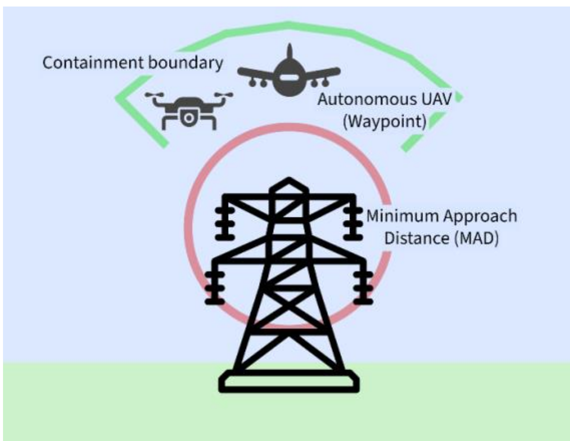

Figure 4: A Representation of EMF Sensor Autonomy.

1.2 Sensor Interface and Interference

EMF detectors measure radiation in a particular area. EMF meters and monitors can perform two kinds of EMF measurements: broadband and frequency-selective measurements [42]. Broadband devices sense a wide variety of signal frequencies. Frequency-selective measurements use a field antenna and a receiver to test for a specific range of frequencies. Because radiation is invisible, EMF sensors must detect abnormal amounts, especially along power lines.

Table 5: Cause and Effect of Various EMFs [42].

Types of EMFs	*Causes*	*Effect*
Natural	- Buildup of electricity in the atmosphere - Earth's magnetic field	Disturb the alignment of the compass or GPS navigation system
Low-Frequency	Power transformers and high-voltage cables	
High-Frequency	Modern communication equipment	

2. Autonomous navigation model

Waypoints are based on calculated distance and angle to a tower in addition to using GPS. The UAVs' distance to the power line and the direction is automated when power line tracking is activated. Waypoints for one tower can be applied to all other towers. Rather than individual waypoints for the entire power line inspection project, only one is necessary, saving flight planning time for drone pilots. Although full automation would benefit the workers in the inspection, the inspector's expertise is believed to be more vital. It is recommended that these UAVs with EMF sensors incorporate semi-autonomous operations utilizing human piloting skills and data collection [41].

3. Power Line Fault Identification

An essential part of the ENLIGHTEN system is the extremely high-speed detection of power line irregularities. This requires multiple Deep Learning (DL) models that can each process information from sensors and discern the state of a powerline segment within milliseconds. The results of each DL model would then be leveraged to evaluate if a powerline abnormality exists. This section identifies filtration techniques and DL models to evaluate power lines.

3.1 Sensor Data Augmentation

For a DL model to correctly identify powerline anomalies, its data input must first be preprocessed, by correcting or removing inaccurate, incomplete, and unnecessary data, as the sensors cannot always provide perfect data. Many research papers have already been written on detecting powerline failure with each of these sensors, and their techniques and technologies can also be used in the ENLIGHTEN system. The various data filtration techniques and algorithms are listed in Table 6.

Table 6: Data Processing Techniques for Each Sensor.

Sensor	Preprocessing Techniques	DL Model/Algorithm used
Thermal Camera	Wallis filter [43] • Increases contrast in low-contrast thermal images by locally adjusting the brightness of individual parts of the image.	Convolutional Neural Networks (CNN) [46] • Uses images from thermal cameras (in conjunction with optical cameras, etc.) to identify patterns and faults in towers/power lines.
LiDAR	Point Cloud Segmentation [44] • Involves Classifying points in the point cloud from raw LiDAR data. Point Cloud Line Extraction [44] • Involves detecting lines and geometry from point cloud data. Terrain/Vegetation data removal [45] • Removal of points not related to above-ground objects.	Power Line LiDAR-based Detection and Modeling Algorithm [44] • Uses point cloud segmentation to map and detect power lines and clusters. • Generates a mathematical model for the power line by graphing a line and catenary. • May detect faults by comparing power line models in an area.

3.2 Model Training & Optimization

One major obstacle in the development of the CNN is acquiring and labeling enough training data. Without enough data to train the DL model, the HSUAV won't be able to properly identify a power line anomaly. One solution is to use synthetically generated data to initially train the model and then use a small set of real aerial data to fine-tune the model. The use of real aerial data is necessary, as some studies have shown that synthetic data cannot fully replicate real data when measuring total model accuracy [47]. Real aerial data can also be used to test the accuracy of the model [47]. One study used the PIL and OpenCV Python libraries to create rudimentary 2D shapes of top-down urban area views. The purpose was to train a DL model to count residential living areas in urban environments [48]. This technique may not completely fulfill the requirements as powerline anomalies cannot be represented just by simulating basic 2D shapes. One solution to this that has come up in recent research is the use of game engines to simulate 3D environments. One study used Unreal Engine 4.27 by Epic Games to procure realistic 3D images of urban buildings [47]. Another game engine named Unity was used to programmatically render hundreds of test images [49]. One advantage of using a game engine is it can simulate real-life camera and light conditions which can help vary the data and train for edge test cases like fog or nighttime operation [49].

C. UAV Charging using Power Lines

A significant limitation of current multi-rotor UAV technology is flight time, limiting the scope and extent to which the UAV services. Yet, power lines are widespread across the United States and serve as a much more accessible power source than large-scale charging pads or stations, requiring new infrastructure and adding to the cost of implementing ENLIGHTEN. The UAVs can locate and recharge using nearby power lines by being equipped with an energy harvester (see Figure 5), a rectifier, and a buck-boost DC/DC converter.

To begin, the UAV positions itself below a power line through LiDAR technology and EMF sensing. After locating a 12 cm frame in which the power line is situated, a gripping mechanism with strong magnets latches onto the line and holds the UAV through magnetic force. The harvester (see figure 5) can then confine the surrounding magnetic field generated by the AC current using ferromagnetic materials and subsequently create an electromotive force in the core to charge the UAV. Simultaneously, the rectifier collects AC currents from the power line and converts them into DC before utilizing the buck-boost to charge the battery. A buck-boost converter allows the drone to take on different input voltages while maintaining the same output voltage [50].

However, due to the high voltages of overhead power lines, the inner electronics of the UAV are subject to surge damage from excessive power. Overvoltage protection on the rectifiers combats this and increases the longevity of such technologies. In terms of efficiency, this system has been proven to retain around 91% of energy [51]. However, future research can improve this efficiency and develop more accurate ways for the UAV to latch onto lines.

This feature drastically improves total flight distance and allows the UAVs to perform more involved inspections. Yet, this form of recharge also comes with its risks, the most prominent being the risk of damaging power lines. The latching design is equipped with arms around 15 cm apart, allowing for up to 7.5 cm of misalignment [52]; however, a slight risk remains, which could lead to devastating effects. Charging stations can still be implemented along with overhead power line charging to reduce this risk.

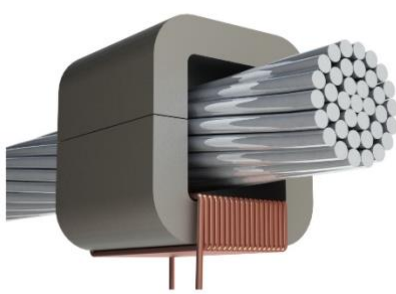

Figure 5: An Illustration of the Energy Harvester (Image credit: Muñoz-Gómez) [51].

V. Discussion

A. Natural Disaster Relief

ENLIGHTEN can be applied in many scenarios for quicker relief and recovery. This section will explore the use cases of ENLIGHTEN in natural disaster relief - specifically winter storms, hurricanes, flooding, and wildfires.

1. Winter Storms

Winter storms occur abruptly with little time for preparation. However, the aftermath of this can be efficiently mitigated through rapid data collection of conditions surrounding power and communities affected, as the high-speed aspect of ENLIGHTEN reduces the need for human intervention and endangerment. During normal conditions, UAVs can track power lines by sensing the electromagnetic waves emitted along with LiDAR and perception devices [53]. However, after freezing occurs, road conditions are often too dangerous for human workers to inspect fallen power lines.

The data from various sensors would be used with machine learning models (see section B3 in “Approach”) to determine whether a power line failure has occurred. After a power line failure is detected, the UAV autonomously conducts a preliminary assessment of the situation and transmits insights about a failure for humans to analyze and determine upcoming procedures. The UAVs would be able to compare previous data with the post-disaster data to detect anomalies efficiently.

2. Hurricanes/Flooding

As discussed in the introduction, hurricanes and flooding have affected power line systems extensively. Regarding hurricane detection and vulnerable power lines, LiDAR technology would be integrated to detect potential anomalies in power lines [54] while also measuring humidity and wind speeds through Doppler shifts [55] from molecules in the atmosphere [56]. Furthermore, this system would be beneficial for obtaining and leveraging power line data after hurricanes for damage assessments. With high speeds, the drones can move through power lines quickly and detect anomalies while ensuring that they maintain power.

3. Wildfires

Wildfires can be detected early using infrared imagery, smoke data, and autonomous inspection. Thermal sensors analyze temperature variations, which allow first responders to identify hotspots in power lines [57]. Additionally, accurate smoke data can be collected through LiDAR by taking air samples [58].

After the wildfire occurs, the power infrastructure of surrounding communities becomes critically disrupted due to the extreme temperatures against the transmission grid, making the areas unsafe for workers to operate hands-on. However, UAVs with navigation systems can sense power line distances and electromagnetic waves using EMF devices [59] and use the resulting data in a machine learning model (see section B3 in “Approach”) to develop an autonomous assessment of power lines. The UAVs would then safely transmit accurate data and insights to workers.

B. Feasibility/Cost/Areas of Implementation

ENLIGHTEN can significantly aid in power line inspection and disaster relief, improving safety, accuracy, and efficiency. With a rapid increase in climate change-related disasters, the U.S. needs help to keep up with sufficient disaster relief. A Journal of Climate Change and Health paper estimates that the U.S. has spent over $2 trillion on secondary costs to natural disasters from 1980 to 2021 [60]. ENLIGHTEN will have a high initial cost but low operating costs, leading to a high long-term return. This system's flexibility allows it to improve and update, decreasing operating and maintenance costs continually. Compared to the staggering costs that the U.S. is currently experiencing due to climate change, natural disasters, and energy infrastructure, ENLIGHTEN will not only minimize those costs but also reduce risk factors, increase efficiency in energy maintenance, and improve safety standards across the energy industry. Comparatively, ENLIGHTEN is feasible to implement across the United States but may be challenged with legal procedures and debates involving ethicality and privacy concerns.

UAVs with advanced sensors can be used worldwide, especially in developing countries. Although countries with existing power infrastructure would have a noticeable benefit, certain countries in South America, Asia, and Africa can use drones for humanitarian and improvement purposes. Power transmission lines will improve due to better inspection, and societies worldwide will enjoy a more reliable power grid.

C. Implications of Implementation

A robust UAV system like that of ENLIGHTEN would profoundly impact many aspects of power line systems, including workers, general maintenance, and disasters.

ENLIGHTEN would significantly improve safety for power lines and construction workers, especially in natural disasters. Drones reduce the complexity of inspections by taking out equipment that would be required for traditional methods. It also reduces labor costs by 30% to 50% [61]. Drones offer a low-cost method to collect high-quality data after a disaster, so it also saves money during a major event. This allows responders to rapidly react to situations through alert systems [62].

D. FAA Legal Action and Procedures

Because this paper incorporates aspects of the European Union-funded AERIAL-CORE project into the United States, part 14 of the Code of Federal Regulations (CFR) must be considered for compliance with the Federal Aviation Administration (FAA). 14 CFR Part 107 lists the procedures that the FAA requires for unmanned aerial vehicles [63].

1. Small, unmanned aircraft are less than 55 pounds on takeoff.
2. UAVs can fly up to 400 feet above ground level unless flown within a 400-foot radius of a structure.
3. When UAVs operate in airports under Class B, C, D, or E airspace, it is required that these drones have clearance from air traffic control.
4. The weather minimums for unmanned aircraft are three statute miles visibility, 500 feet below clouds, and 2,000 feet horizontally from clouds.

VI. Future Considerations and Conclusion

Countless disastrous weather events occur yearly, along with inefficient energy maintenance, affecting the electrical grid and costing billions yearly.

In the future, ENLIGHTEN can be expanded to be fully autonomous and improve the safety of people working alongside utilities and customers. For example, the UAV system could be integrated along with the Integrated Public Alert and Warning System used by the United States for weather and safety alerts. Autonomy among the system could allow the drone to expand beyond only collecting data and play an active role in problem-solving during disastrous times. This could mean the addition of a custom machine-learning model with multiple sensor inputs for efficient and low-stress computations. Yet, beyond the U.S., countries worldwide can experience power loss for weeks or months at a time due to the less developed energy infrastructure, warranting the need for the ENLIGHTEN UAV system to be implemented worldwide to provide disaster relief.

This paper expands on current research and proposes using HSUAVs to address this problem by observing, inspecting, and acting on power lines. ENLIGHTEN uses GPS and EMF sensors for navigation, thermal imaging for power line fault detection, and a recharging system through nearby power lines for extended-ranged inspections. A Raspberry Pi would be used to process data for navigation and detecting faults. Digital twin applications, wind tunnel testing, and PID tuning will also test and refine the system's stability. This new UAV system would significantly help overcome the power line maintenance challenges created by natural disasters to help prepare for the future of energy infrastructure.

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