Wireless Energy transfer to long distance flying Intelligent Unmanned Aerial Vehicles (UAVs) using reactive power transfer techniques

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***Abstract*—Wireless power Transfer (WPT) to Unmanned Aerial Vehicles (UAVs) is promising to be a ground-breaking technique for efficient charging of long-distance flying UAVs. WPT allows the power to be transferred directly from a ground station to a long-distance flying UAV eliminating the need for UAVs to carry batteries as the source of power whose heavy weight affects the duration of UAV's flight. This paper first reviews the recent application of Wireless Power Transfer to UAVs and highlights advantages of using this technique for economic and efficient design of intelligent autonomous long-distance flying UAVs. The paper then discusses the need for the fusion of the sensors used in WPT and IMU sensors used in UAVs, the use of deep learning algorithms in long distance flying UAVs, and highlights the factors that affect the safety and reliability of long distance power transfer to UAVs. The work described in this paper is part of the authors' research project that aims to investigate and develop sustainable autonomous unmanned aerial vehicles. The progress being made so far in implementing Reactive wireless power transfer techniques (RWPT), the potential future works, and the envisaged associated challenges are reported in this paper.**

***Keywords*—Unmanned Aerial Vehicle (UAV); Wireless Power Transfer technique (WPT); Drone; Energy; Autonomous System; Sensor-fusion; Reactive wireless power transfer techniques (RWPT);**

I. INTRODUCTION

Wireless Power Transfer (WPT) as a charging method is currently being extensively used for objects such as mobile phones, headphones, small gadgets, etc. This technology, however, is not being commonly and commercially used for charging of the unmanned aerial vehicles (UAVs) or electric vehicles because of the huge loss of power involved when the energy is wirelessly transferred from WPT's device to the UAV's batteries. But since the Wireless Power Transfer allows the power to be transferred directly from the ground station to a UAV, through the natural air medium, without wires, there should not be any need for the UAVs to carry heavy weight batteries anymore. As such the use of WPT systems for Wireless Transfer of power to UAVs could create a mass market opportunity. The first WPT system was discovered by a famous scientist named Nikola Tesla [1] in 1890. He also patented many wireless power transmission applications at that time, making him the true founder of wireless electricity, but that technology never became a commercially available technology because of the lack of sufficient financial support he needed in his time. The use of WPT in UAV research is already being carried out by many researchers [2-5] but, due to some technical limitations reported by the researches, the technology has not yet been proved economically feasible or technically efficient for embedding in the Design of intelligent long distance flying UAVs, especially in cases where the UAVs required to fly over a long period of time demanded by particular applications. The various methods of wireless power transfer being reported in literature can be categorised based on particular techniques they have used, five well known techniques are; (1) Electromagnetic Induction [7-10], (2) Electromagnetic Resonance [11-14], (3) Electrostatic Induction [15], (4) Use of Microwave technology [16], and (5) use of laser wave technology. Some of these used long wave transmission (5-6) and some covered short wave transmission (1-3). This paper provides detailed discussion of the use of Electrostatic Induction (category 3), and also the combined use of the categories; (1) Electromagnetic Induction, (2) Electromagnetic Resonance, and (3) Electrostatic Induction.

Jenn, D [19], extensively researched and experimented with short distance wireless power transfer for UAVs using electromagnetic induction methods with over 90 % efficiency. His work established that the near field, short distance wireless power transfer technology has already been applied to UAVs successfully but for long distance flying drones this has not been so, and also the technology is not safe and reliable because the microwave and laser wave transmissions have poor efficiency in extreme weather conditions [20], hence dangerous to human beings [21].

Various types of UAV classification are shown in figure 1 [23]. This paper is focused mainly on VTOL (vertical take-off and landing) type of UAV because this craft currently uses batteries to operate in Low Altitude Platform (LAP), and can easily be integrated with the WPT system. LAP category UAVs fly below 15km height whereas the High Altitude Platform (HAP) category UAVs fly 15 km above sea levels.

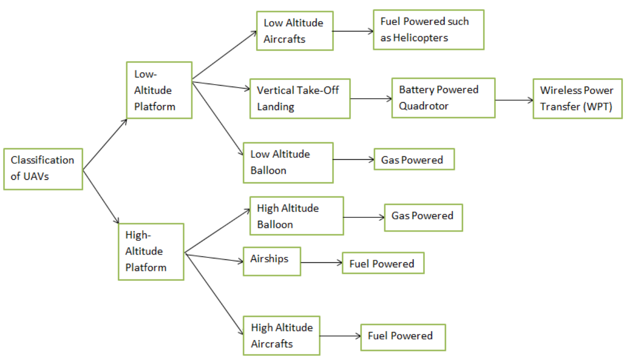
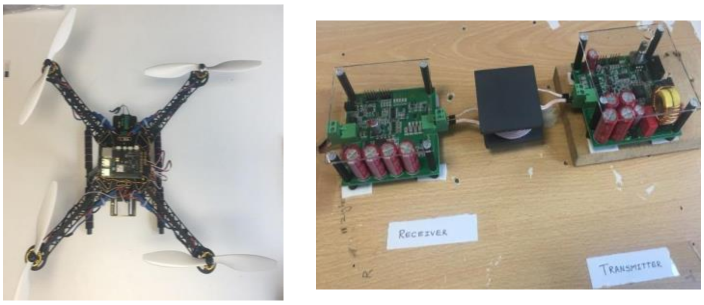


Figure-1 UAV altitude platform classification and this review focusing on VTOL type WPT

Furthermore, WPT techniques can enable faster communication with UAV, avoiding using inefficient radio communication

The work presented in this paper is part of the research project that aims to investigate and develop sustainable autonomous unmanned aerial vehicles. The project also investigates application of sensor fusion and deep learning algorithms on UAVs aiming to fuse WPT sensors with IMU (inertial measurement Unit) sensors and deep learning algorithms for long distance flying UAVs, which is an innovative novel approach. For our research experiments we use a quadcopter we developed (shown in figure-2a) and a 200 watts Wireless Power Transfer (WPT) kit (shown in figure-2b).



(a) (b)

Figure-2 (a) Quadcopter with Raspberry Pi 3b and Navio 2 Flight Controller Module used to test with (b) a 200 W Wireless Power Transfer Module

II. Description of Wireless Power Transfer Reviewed

A. *Electromagnetic Induction*

Electromagnetic induction is currently used for short range wireless power transfer operation. The working principle is that alternating current is applied to the transmitter wire coil which is inductively coupled with receiver coil using magnetic field. Output power is then transferred through a rectifier to get usable DC power to the drone. There are studies on the drone battery charging using electromagnetic inductive coupling method [23] and efficiency of the coupling is calculated using coupling factor equation [24]. Moreover, the total coupling coefficient exists between transmitter coil and receiver coil shown below;

$$k = \frac{M}{\sqrt{L_T L_R}}$$

Where, k = coupling factor between transmitter (TX) coil and receiver (RX) coil, M = mutual inductance between TX and RX coil, L_T = TX coil inductance, L_T = RX coil inductance

B. Electromagnetic Resonance

Electromagnetic resonance coupling method also uses inductive coupling method, but power transfer is tuned by using magnetic resonance at a tuned frequency between transmitter and receiver inductive coils. The reason for using resonance inductive coupling is that huge power losses occur because leakage inductance occurs around TX and RX when sending higher power. Nikola Tesla [25] discovered this method and later experimentally proved it by the MIT team [26] in 2007 by sending 60 watts of power using resonance coupling successfully to 6 and half feet distance with a half efficiency. When using extreme frequency, there will be resistive loss occur between TX and RX coils which can be measure as follows;

To find Inductive Resonance coil resistive loss [27]:

$$R_{losses} = \sqrt{\frac{\omega\mu_o}{2\sigma}}\frac{l}{2\pi a},$$

Where R_{losses} = resistive loss, ω =angular frequency, $\mu_o = 1.2566\times10^{-6}$ (vacuum permeability), σ = 592×10^5 S/m(copper wire conductivity), l is the length of copper wire, a = cross-section area

When resistive loss is directly proportional to the skin depth [28] of the coil shown below:

$$\delta = \sqrt{\frac{2\rho}{\omega\mu}},$$

Where δ = skin depth of the coils, μ = effective permeability, ρ = resistance of the copper coil

C. Electrostatic Capacitive Coupling

Electrostatic capacitive coupling method [29] can be defined by two capacitive connected with both transmitter and receiver form a capacitance between them which help transfer energy to the transmitter load. This type of transmission is possible by using high frequency alternating current oscillating between transmitter plate and receiver plate, which activates electric flux between them. The power received in the receiver plate is then converted into Direct current by adding a full bridge rectifier circuit into the system, so the load can be used afterwards.

D. Microwave Wireless Power Transmission

In the mid-20th century, a microwave oven was invented [30] which is still today for heating up things. Microwaves are high frequency waves which are a form of electromagnetic waves. Electrical energy from the transmitter is converted into microwaves by using magnetron [31] and then transmitted to the antenna which will then send wireless microwaves into the receiver antenna with the same setups. This method was proven by William C Brown [32] who successfully transmitted wireless microwave electrical energy. This method is recommended to use outer space power transmission because of long distance power transmission compatibility. The disadvantages of using this method to transfer energy is extremely high frequency current radiation which can harm animals and human beings if they interfered between transmitter and receiver of microwave power transmission [33].

E. Laser Powered Wireless Power Transmission

Laser radiation can cause extreme heat on nearby pointed [34] surfaces because photons inside lasers are so dense and powerful. The working principle of laser powered WPT system is that a high-power laser pointer acts as the transmitter which receives laser power as heat energy which can be converted into electric current [35]. Solar panels can also act as a receiver which will store electrically energy when a laser is transmitted in air or free space [36]. Laser power is more powerful than the sun's energy when using photovoltaic cells. This method will work day and night without any huge power losses [37]. Currently, there is only the microwave WPT method and laser WPT method can transfer energy long distances.

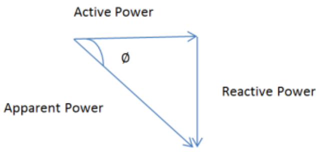
F. Active and Reactive Power Transfer in WPT

As the intensity of wireless power systems builds up, the use of active and reactive power transfer methods become important to maintain stable power transfer by adjusting their frequency and voltage evenly [38]. Active power is the main usable power for a circuit whereas reactive power is only transferred between transmitter and receiver without giving any usable power to the circuit [39]. Active and Reactive Power initiates in the circuit just 90 degrees behind the applied voltage by a point of pi (Φ) which is the apparent power [40].

Figure-3 Difference between Active and Reactive Power

To find active power (P) of a circuit using below equation,

$$\mathrm{P(watts)} = \mathrm{VI}\cos\emptyset = \mathrm{I}^2 R,$$



Where, V = voltage of the circuit, I = current, □ = angle between apparent and active power, R = resistance

To find reactive power (Q) of a circuit using below equation,

$$\mathrm{Q(VAR)} = \mathrm{VI}\sin\emptyset = \mathrm{I}^2\, VAR,$$

Where, VAR = voltage ampere reactive.

Although reactive transfer is not usable power, it can help transfer active wireless power long distances back and forth using tuned resonant frequency between transmitter and receiver which can connect with earth ground itself using the theoretical approach presented in this paper.

III. BACKGROUND UAV DEVELOPMENT

From the 18th century, research activities in the use of unmanned aerial vehicles increased tremendously by only militaries for the purpose of war in various countries [41]. As a result, aerial photography was also used primarily in order to monitor the enemy's area. By the late 1930s the US navy experimented with a project to develop a remote controlled UAV that could be used for long distance control. This work eventually led to the development of the first ever remote control unmanned aerial vehicle during world war 2 [42]. However, these aircrafts required a human to constantly monitor, guide and control the motion of the drone. With pressing needs for high altitude and low cost, the UAV was able to be used in fleet operation by Israel Air force in the late 1980s [43]. These new UAV technologies lead to the creation of low-cost UAV for fleet operations to carry out a variety of tasks automatically by United States Airforce in 1986 [44]. At the end of the 19th century, small UAVs were developed and monitor the activities of terrorists in remote areas [45]. In the early 21st century drone delivery experiment was done by the various cooperatives of these machines could be significantly enhanced using extra fast package delivery [46]. This method coupled with advancements in computer vision technology has led to increase in UAV development and in recent years [47].

A. *Wireless Powered UAVs*

Some of the batteries powered commercially available aircrafts in industry use the wireless powered UAV and links to charge UAV's battery each time by landing the aircraft to the transmitter coil [48]. In some battery powered WPT aircrafts running today, they are still using electromagnetic resonance methods for cost effectiveness but the efficiency and distance between the transmitter and receiver are very low [49]. The WPT of the aircraft needs the long-distance wireless power transfer to fly without landing for each charge. The microwave and laser powered wireless aerial vehicle which would harm humans or birds to fly in air against radiation caused by these extreme frequency wave transfer methods [50]. These types of wireless power transfer technology require efficient solution of the cost-effectiveness and safety of the environment.

The primary UAV wireless power transfer system consists of the following;

- Electromagnetic Resonance wireless battery charging of UAVs [51].
- Microwave Power Transmission of electricity using high frequency antennas to transmit power to aerial vehicles [52].
- Laser power transmission of electricity to UAV receivers in the same method solar panels method [53].

B. *Short Distance Electromagnetic Resonance Wireless Powered UAVs*

Electromagnetic resonance coupling method works at a tuned resonant frequency between transmitter and receiver inductive coils which are connected to the load (UAV) [54]. Whenever the UAV battery becomes low, the UAV which already has installed the receiver coil connected to the battery goes down to the exact place where the transmitter resonance coil is located and lands over it to recharge itself. When the full power is taken, the UAV continues its operation by taking off from the transmitter coil [55].

C. *Long Distance Microwave Powered UAVs*

Since all wireless powered aircraft use the same method to power the entire circuit, sensors and actuators of the UAV [56], that is the motors are powered by energy storage and controlled by speed controller devices and micro-controllers. For long distance and space UAV operation, microwave wireless power transfer method can reach the longest range because of electromagnetic wave transfer which travels at light speed in vacuum [57].

The principle of microwave WPT UAV technology is that electricity is first converted into high frequency using traditional microwave magnetron transformers [58]. Using the same antenna design as radio techniques to transfer microwaves to the receiver antenna located in UAV with same resonance microwave frequency. Figure-3 is a block diagram illustration of the basic microwave electric powered UAV propulsion system. The UAV system starts by powering the motor and throttling the motor speed by controlling voltage input of the motor which makes the propeller rotate and cause thrust and airspeed using energy from microwave wireless power. Although the system looks simple there are several different power configurations mode and safety issues [59] according to the application and difficulty in flying in extreme weather conditions [60].

D. *Long Distance Laser Powered Wireless UAVs*

The working principle of laser powered WPT system for UAV is that a high-power laser pointer acts as the transmitter which receives laser power as heat energy which can be converted into electric current [61] transmitted into load which itself is UAV. Figure shows that multiple UAV is powered using laser WPT transfer which is discussed in paper [62]. Advantage of using this method is that high power can be transmitted using laser power which is lower than microwave UAV wireless power transmission system [63]. Drawbacks are laser radiation is highly dangerous living beings and transmitter and receiver should be always in sight for efficient power operations [64]

IV. The Design Of Reactive Wireless Power Transfer (RWPT) System For UAVs

Nikola Tesla patented the first design of wireless power transfer around the 1900s [1] using earth surfaces as a ground and high-pressure atmosphere as a conductor to transfer electricity from one distance to another. Even this closed-circuit design may work, if we want to apply it practically would be impractical and risk clashing communication with passenger flights because we must raise a hydrogen balloon to the height above sea level of more than 30 thousand feet. Tesla proposed not only that earth atmosphere become conductive like wire when it reaches certain pressure levels but also using reactive power transfer method to send electricity using only ground. When the Reactive power transfer method oscillates between transmitter capacitor and receiver capacitor using resonant tuned frequency, there would be standing wave pressure build up between transmitter and receiver which helps transfer usable active power to the UAV.

In this design, reactive power transfer method works at half of 360 degree between two capacitors. Once main active power activated, the power converted into reactive power by using quarter wave coils between transmitter and receiver. Quarter wave coils purpose is that the circuit should be in resonance to transfer power efficiently. When the power is activated, two capacitors exchange reverse charges simultaneously using reactive wireless power transfer method. Then, standing waves between transmitter and receiver ground formed and usable power transmitted into the UAV or load shown in figure-5. Other type methods can be used for transmitting power through one wire transmission on UAVs for the purpose of showing the working principle of RWPT system. The circuit was tuned in the same way as using electromagnetic resonance. For the efficient power transfer method, the UAV frequency also should be in resonance with the RWPT circuit.

A. *RWPT UAV Of the Future*

Despite the great deal of research work done in the field of WPT and unmanned aerial vehicles and the advancement in its technology many experts agree that one of the major drawbacks of today's WPT UAV is that they tend to use extreme power usage, charging batteries usually takes out operation time, low range wireless power transfer and complexity of the resonance transmitter and receiver coil designs. An important consideration in connection with the WPT UAV system is that the power can be transmitted using the same earth ground in which large amounts of electrons stored inside and capacitive coupling approach to the UAV which it would act as a return wire instead of sending through air. In the practice of building traditional WPT systems in UAV, structures which tend to cost high and are often used to provide complicated design required for different applications. To achieve the required long-distance operation for WPT UAV, an electrostatic capacitive coupling method can be made in terms of using earth ground as conductor with desired resonant frequency are used for the UAV which would result in the power travel faster and further.

This capacitive coupling system can be used to transfer energy to not only UAVs but also any types of battery powered system can be integrated to use this method. The 'space' between the capacitor plates or spheres and air which is also as dielectric for charging and discharging electrostatic power That is, the region changed into a state against which a mechanical push could be applied. This suggested, utilizing this procedure, it ought to be conceivable to create a transmitter plant in desired area and receiver can be far away from the transmitter, if the earth resonant frequency and TX, RX resonant frequency can be tuned to work in same which could be resolved the issues of long-distance power transfer. Further investigations and experiments needed to prove these methods wireless power transfer method of UAV.

Conclusion

Fast evolving technologies have led to the innovation of powerful wireless powered unmanned aerial vehicles (UAV), also known as WPT drones, for the purpose of working in dangerous environments which humans aren't able to travel. In this paper we reviewed the background of UAVs, existing wireless powered UAV, the working Principle of Wireless Power Transfer methods including short- and long-range methods, finally the future of WPT transfer using electrostatic resonant coupling method using earth as a return wire. Future papers, we will be experimenting with this method to power the UAVs efficiently, the safety and reliability of sending power to longer distances.

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