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Near-field Wireless Power Transfer Technology for Unmanned Aerial Vehicles: A Systematical Review

Xiaolin Mou, Daniel Gladwin, Jing Jiang, Kang Li and Zhile Yang

***Abstract*—Unmanned Aerial Vehicles (UAVs) technology has seen a significant boost in the past ten years and has been widely adopted in entertainment, rescue, intelligent transportation, no-touch delivery, environmental monitoring and other real world applications. However, the ranging limitation due to the shortage of battery energy capacity remains a major issue hindering further development of UAVs. Wireless power transfer (WPT) technology is a new technology of great potentials in improving the endurance of UAVs. The integration of WPT into UAV not only activates the recharging of UAVs batteries, but also enables UAVs to recharge other devices. Moreover, wireless charging technology allows the device to be fully enclosed and suitable for harsh weather conditions. This paper presents a comprehensive review in regard to the state-of-the-art of near-field WPT technologies for UAV charging, including technologies characteristics, design issues, as well as multiple case studies. A comparative analysis of existing technologies are also presented, associated with key future research discussions of WPT for UAVs.**

***Index Terms*—Unmanned Aerial Vehicles (UAVs), Wireless power transfer (WPT)**

Table I: Examples of various capacity UAV

<table>
<tr><th colspan="3">Military UAV</th><th colspan="3">Entertainment UAV</th></tr>
<tr><td colspan="3"></td><td colspan="3"></td></tr>
<tr><th colspan="2">Delivery UAV</th><th colspan="2">Fire Fighting UAV</th><th colspan="2">SureFly Vehicle</th></tr>
<tr><td colspan="2">
WORKHORSE</td><td colspan="2"></td><td colspan="2"></td></tr>
<tr><td colspan="2">Maximum Speed: 46 statute miles per hour
Battery Pack: 40000 mAh battery pack
Payload Weight: 10 Pounds</td><td colspan="2">Max.Take off weight: 45kg
Battery Pack: 44000 mAh
Max. endurance: 35 mins</td><td colspan="2">Power System: Hybrid Power
Maximum Speed: 110km/h
Payload Weight:180 kg</td></tr>
</table>

I. INTRODUCTION

The Unmanned Aerial Vehicle (UAV) technology is quickly evolving in recent years due to continual cost reduction and increasing performance [1]–[3], adapting to a wide range of new applications. UAVs are widely used in commercial, military, government and other scenarios. The military market alone is expected to increase by more than 50% over the next fifteen years [4]. It will be made on acceleration of the replacement of human pilot utilizing UAVs in the wars. In addition to military segment, the entire drone industry is also expected to see explosive growth [5].

Depending upon the specific applications, the UAV models has variable sizes and designs [6]. They can be grouped into fixed-wing UAVs and rotary-wing UAVs. Rotary-wing UAVs are commonly designed with single or multiple rotors, the more motors an UAV has, the higher lifting power it gains [7]. The example of various capacity UAV as shown in Table I. Though initially developed for the military use, UAVs have now been used in many civil areas to accomplish various intractable in-air tasks such as aerial photography, agriculture, and power system repair maintenance [8], [9]. Beyond that, the use of UAV is extending. One of the most promising applications of the UAVs is the package/parcel delivery. The HorseFly package delivery UAVs by Workhouse [10], where a 4-rotor UAV that can safely, efficiently complete daily package delivery. The whole delivery system is integrated with the electric delivery vehicle. UAVs delivers packages for those within the last mile distance and get back onto the trucks to pick up new packages along the route. UAV No-Touch Delivery also plays an important role during Covid-19. In India, drones have the ability to play a key role in combating the coronavirus. Drone startups in India work alongside authorities providing services such as disinfecting contaminated areas, managing crowds and delivering medical supplies [11]. SAR (Search and Rescue) UAVs are another important application which efficiently scans vast areas and identifies victims rapidly, such as the fire fighting UAV. The fire fighting UAV can fast solve the fire rescue for high-rise buildings [12]. They are equipped with thermal imaging cameras as well as infrared cameras. In addition to above two applications, people mover UAVs is a futuristic application that will be developed rapidly in aerospace market. MooG has proposed the Surefly vehicle [13] incorporating hybrid power systems and four lithium battery packs backup power to drive its eight motors, through which the traffic pressure can be efficiently eased.

The UAVs use different types of specific power sources to meet the power requirements of on-board equipments, such as solar cells, hydrogen-enriched proton exchange membrane fuel cells, and laser technology [6]. However, the most commonly used technology is the lithium-ion or lithium-polymer batteries [14], accounting for over 96% of commercial and personal UAVs [15]. Overall, 20-30 minutes is the current available UAV flight time [16]. However, the time of UAV can fly

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depends on the level and model type. To increase the flight time, two options could easily be considered, *e.g.* increasing battery capacity or getting the battery charged. Given the current state-of-the-art battery technologies, the trade-off of energy storage and the mass is hard to achieve, leading to the significant difficulty in increasing proper battery capacity without brining any extra burdens. The second option is to utilize wired or wireless charging techniques to get the battery charged. It is apparent that wired charging may strongly restrict the mobility of UAV. The wireless option therefore becomes an alternative and effective option [17]. Utilizing wireless charging approach, the UAVs do not need to return to the base for charging and are then given sufficient freedom [18]. Moreover, the charging slot is not required in wireless charging technology, so it allows the UAV device to be fully enclosed and suitable for rain/snow weather conditions.

Wireless Power Transfer Technology (WPT) was innovated by Nikola Tesla in 1890 and developed rapidly in recent years [19]. Near-field WPT is a mature wireless charging technology which widely been chosen to use in the existing products such as electronic equipment and electric vehicle [20]–[32]. This paper will focus on reviewing the near-field WPT technology for UAVs application. There are two groups of near-field WPT technology: inductive power transfer (IPT) and capacitive power transfer (CPT) [33]–[39]. The IPT system uses magnetic fields to transfer power, and the CPT system makes use of electric field. The IPT could be fully used as a driving voltage for CPT coupler due to the IPT can transmit high power and voltage across the coils. The CPT has advantages in efficiency reduce the weight of the coupler. Considering the advantages of IPT and CPT technologies, the hybrid wireless charging system was proposed and more suitable for UAVs application. Currently, major manufacturers have started to integrate WPT technology into electronic products. The different technology requirements between the existing wireless charging productions and UAV applications be summarised as follows:

- **Coupler configuration diversification:** the general shape of wireless charging couplers, such as used in mobile phone and electric vehicle is flat coils, the location of transmitter coil and receiver coil is parallel. However, in UAVs application, the location of transmitter coil and receiver is not only parallel, but also can be cross vertically. Moreover, considering the UAVs lander, the shape of coupler is variety.
- **Strict control requirements:** The landing accuracy of UAVs will be greatly affected by the environment (wind) in addition to the device technology, the control of couplers docking is harder than other products. The require of toleration is higher due to the misalignment issues includes both lateral and angle.
- **Lightweight devices:** The weight of WPT device should be light due to reduce the extra energy cost and payload weight. So the high power efficiency electronic devices is necessary. Moreover, the topology of the component circuit should be simple under the requirement of ensuring good wireless charging performance.
- **Reduce Electromagnetic Interference (EMI)**: IPT technology uses magnetic coupling to transfer the energy. The magnetic field will interference the airborne equipment such as camera's normal work, sensors on UAV and communication.

This paper comprehensively review the current states-of-the-art of wireless power transfer technology for UAVs charging which depends the near field WPT technologies: inductive power transfer and capacitive power transfer. Research about hybrid WPT charging design is reviewed which is suitable for wireless UAVs charging in the future. Section II introduces the IPT wireless UAVs charging technology includes coil configuration, landing toleration and control, compensation topology, and safety issues aspects. Section III reviews the CPT WPT for UAVs charging includes coupling interface, compensation topology, and case studies. Finally, this paper provides a comprehensive discussion of their characteristics, design issues, and the future developments of wireless UAV charging.

II. IPT SYSTEM OF UAVS

A typical IPT equivalent circuit as shown in Fig. 1 where V_p is the power supply, R_L is the load resistance, R_1, R_2 denote the internal resistance for the two coils, L_p, L_s represent the equivalent inductance, C_1, C_2 represent the compensation capacitance of the circuit, and M represents the mutual inductance between the primary and secondary coils.

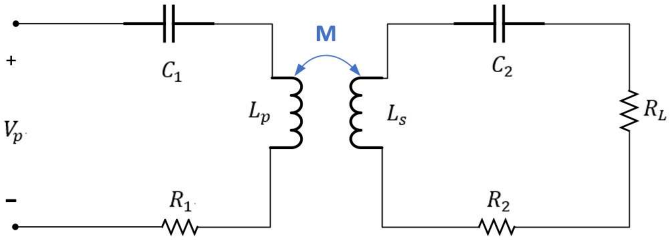
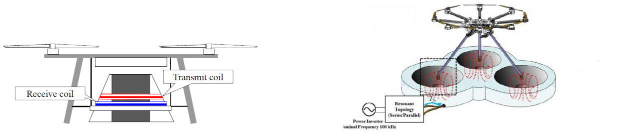


Fig. 1: Equivalent circuit of IPT system

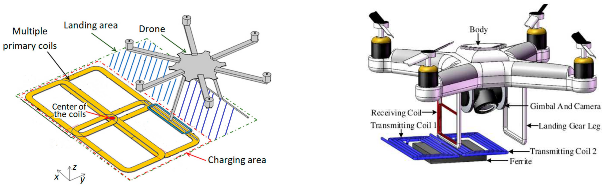
1) Coil Configuration:

The coil configuration for inductive wireless UAV charging has been investigated within the research community. The shape can be roughly divided into two categories: stereo shape (spiral coil) and flat shape (square coil or circular coil), as shown in Fig. 2. The requirements of wireless UAV coupler design such as light-weight, compact structure, and high magnetic capacity. The development of UAV coupler configuration can improve the docking accuracy of two couplers thus improve the power transfer efficiency.

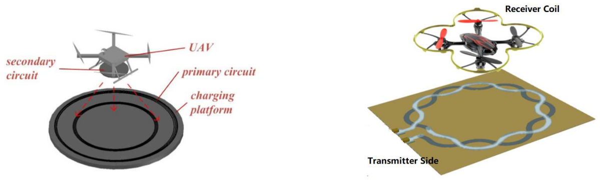
The stereo shape UAV wireless charger as shown in Fig. 2a, which can achieve high receiver power (450 W) for large UAV application. The charger is a truncated four-sided pyramid (frustum type), which is made of non-metal material. The cone is trapezoidal at the top and bottom. Install transmission coil at middle height of frustum.A ferrite plate is arranged in the position where the magnetic flux needs to be concentrated [40] [49]. Compared with the flat type, it has advantages such as light weight of receiver coil, reduce the disturbance by metal foreign object. However, the landing accuracy is



(a) Frustum type structure [40] (b) Square coil-array structure [41]



(c) Coil-array structure [42], [43] (d) Coil-ferrite structure [44]–[46]



(e) Circular coil structure [47] (f) PCB coil structure [48]

Fig. 2: Configuration of UAV Charger

required higher than flat coil, due to the receiver coil should cover the charging port accurately. In addition, Kim *et al.* [50] and Chiuk Song *et al.* proposed helical coils design for transmitter. The three-phase helical coils charger as shown in Fig. 2b. The spiral Litz wire is used as winding on the ferrite core as WPT charger which can provide high permeability and reduce the weight and loss. The system is a three-phase resonant wireless charging system reduces the total harmonic distortion of the Tx and Rx currents by 14.21% and 7.45% [41]. The limitation of this design is low applicability, only for three-legged landers UAV. Moreover, the landing accuracy is higher.

Flat shape chargers are common design. Campi *et al.* proposed a square coil-array charger for UAVs application, as shown in Fig. 2c. The transmitter pad is a coil-array structure which has four independent planar coils placed suitably to entirely cover the charging area. The receiver is a planar coil which placed on the UAV's landing pad. System efficiency can achieve 85% under no misalignment condition [42], [43]. The advantages of this multiple primary coils structure is that the system has a high level of tolerance to misalignment condition. Fig. 2d shows another magnetic coupler for UAV charging which is described by Cai *et al.* [44]–[46]. The transmitter pad has two coils and three ferrite strips, and the receiver coil is wound along the frame of the landing gear. The receiver coil and the transmitter pad are usually arranged in the form of a cross. The UAV will be charged when the landing gear coil with the receiver coil falls on adjacent parts of the transmitter coil. An 600 W implementation shows that the system has a high efficiency and the misalignment within the range of 30 mm [44]–[46]. This structure can efficiency reduce the magnetic resistance and improve the coupling capability.

Song *et al.* [47] proposed a two circular coils connected to the primary coil structure as shown in Fig. 2e. Each circular coil is single layer and shares the same turns. The secondary coil adopts a disc coil structure given the minor load of UAVs. The proposed design keeps the power transfer efficiency at about 91% when the offset distance is less than 200 mm [47]. A large circular primary coil with a small secondary coil structure is proposed to power the UAV is presented by Campi *et al.* [51], [52]. On the on-board receiving side, a small single-turn coil is adopted to replace the original propeller protection. This design improves the misalignment tolerance and remarkably reduce the on-board component weight. Fig. 2f illustrates a PCB circular coil by Aldhaher *et al.* [48]. The proposed two-layer PCB transmitter coil consists of two turns which are shaped such that the minimal overlap between the tracks on the top and bottom layers is achieved. This can reduce the capacitance between the turns which pushes the self-resonant frequency higher, while the receiver coil is series turned. Most of the above researches almost focused on the transmitter coil. Chen *et al.* presents an automatic and high-efficient wireless 3D printed UAV charging with a three circular coil array receiver. Utilizing WPT technology improves the battery duration and relief the misalignment sensitivity. In addition, the complexity of fabrication and total weight of UAV are significantly reduced [53].

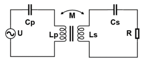
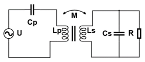
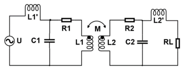
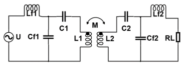
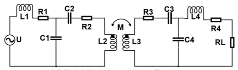
2) *Landing toleration and Control:*

Landing toleration is research challenge in wireless UAV charging, particularly in hover charging status. The methods have been proposed to solve the misalignment problem such as coil matrix structure design, control algorithm development and mechanical method.

The coil matrix structure is proposed by Rohan *et al.*, which can achieve high power transfer efficiency and solve the misalignment between transmitter and receiver in a wireless UAVs charging system [54]. Multiple transmitting coils are designed on a movable bed with four direction freedom. An automatic alignment algorithm was implemented inside a micro-controller, which measures the terminal voltages of each transmitter coil simultaneously, and identifies which transmitter coil has the lowest voltage. The transmitter coil has the lowest voltage, it implies the transmitter coil is close to the receiver coil. A practical test bench was developed for the system and the system was fully automatic and achieved 98.8% accuracy in mitigating poor landing simulation [54].

J. Zhou *et al.* proposed a nonlinear parity-time symmetric model, wherein the nonlinear saturable gain is provided by a self-oscillating controlled inverter. The experimental results show that within a confined three-dimensional volume of space, stable output power to the UAV from WPT platform is maintained with constantly 93.6% efficiency [55]. A hybrid control method called PWM-controlled capacitive variation method is proposed by H. Zhang *et al.*. This method could ensure the UAV's receive stable voltage with horizontal and vertical offset of 200 mm and 62 mm, moreover, the maximum efficiency of this system can arrive 91.9% [56]. Mechanical guidance is one of the common methods of aircraft landing. Shuai Wu *et al.* proposed a position correction system which uses the mechanical for landing accuracy [57]. The advantages of mechanical position correction is simple and reliable performance, however, the accuracy maybe not high.

Table II: IPT Compensation Topologies

IPT Compensation Topology	Characteristics
 (S-S) Series-Series Compensation Topology	S-S topology and S-P Topology are basic compensation topologies. Series compensation topology is sufficient for distance transmission, while parallel compensation is generally regarded as the optimal choice when the primary coil requires large current. In the secondary part, series compensation has voltage source characteristics, thus it is well suited for systems that have an intermediate DC bus. In general, load receiving power and system transmission efficiency of S-S topology is better than S-P topology.
 (S-P) Series-Parallel Compensation Topology	
 LCL-LCL Compensation Topology	LCL compensation topology has better light-load characteristics which can achieve a peak end-to-end efficiency of 96%. LCL compensation topology has a perfectly constant current throughout the entire range of coupling.
 LCC-LCC Compensation Topology	LCC compensation topology greatly simplifies the control complexity in the primary side, and achieve a unity power factor at the secondary side, which leads to high power efficiency. LCC compensation topology has characteristic of constant current both the input and output.
 LCCL-LCCL Compensation Topology	LCCL compensation topology can achieve a high efficiency with a high-power level. LCCL compensation topology can get constant output current at a specific frequency which is not affected by the load and coupling coefficient.

3) *Compensation Topology:*

Compensation circuit topologies are crucial for IPT charging system design. Series-Series (S-S) and Series-Parallel (S-P) are two basic compensation topologies which have widely been used in IPT charging system due to the low complexity. The LCL, LCC and LCCL compensation topologies are hybrid compensation topologies. The summarised compensation topologies are shown in Table II [58]. This part focus reviewing the selected compensation topologies used in UAV application.

Because the output current of lithium battery charging is constant, S-S compensation method is adopted [57]. C. Cai *et al.* choose the S-S compensation topology for their 500 W UAV wireless charging system, and the pick-up structure is the sample which can minimize the weight of pick-up in UAV side [46]. The S-P compensation network was used in Gordhan's work due to S-P can realise a constant-voltage and a constant-current output [59]. T. Campi *et al.* compared S-S compensation topology and S-P compensation topology in IPT UAVs charging system. The results show that under the same turns of the primary coils, the efficiency of the S-S compensation topology can get 89% which is higher than S-P compensation topology [51]. However, S-P compensation topology can reach a higher efficiency when the turns of secondary coils are less than S-S compensation topology [43]. C. Cai *et al.* proposed a LCL-S compensation topology which is suitable for the low voltage and high current UAV charging system [44]. LCC-S compensation network can achieve a constant primary side current to prevent primary side overcurrent damage and fulfil the lightweight requirements of UAV side [60]. U.Kavimandan *et al.* proposed the sensitivity comparison analysis with LCC-S topology and LCC-P topology [61]. It was found that the effect of the magnitude of the input impedance with LCC-P topology was significantly lower compared to the LCC-S topology. In addition, LCC-P can reduce the switching loss. However, when the coil is obviously not on time, the input current compensated by LCC-P will increase. The LCC-P topology looks not the best choice for UAV application. It can be found from the above research, the basic compensation topologies (such as series-series topology) are used at receiver part are reckoned as the better option considering the weight of pick-up in UAV side.

4) *Safety Issues and Renewable Power Supply:*

The electromagnetic interference (EMI) is one of the concerns in IPT technology, particularly the components in UAV are vulnerable to electromagnetic effects. However, it will increase the weight of UAV if the additional shielding is mounted on the UAV. Song *et al.* [62], [63] has proposed an automated resonant WPT charger for UAV. The power load of UAV is 200W and the frequency works at 100 kHz. The results show that the proposed UAV charging system reduces the total harmonic distortion of Transmitter and Receiver currents by 14.21% and 7.45%, respectively.

Li *et al.* and Wang *et al.* [64] proposed a wireless UAVs charging system powered by solar panel. The system is powered by a solar panel and can work off the grid at remote areas. A test platform was built where the input DC power is 48 V and frequency is 100 kHz. The transmission efficiency is 91.2% when the receiver coil has no magnetic core and 96.5% when the receiver coil has a magnetic core, respectively. Both cases did not consider displacement and air gap status. Ali *et al.* [65] proposed a cost effective automatic recharging solution for UAVs. The authors developed a GPS vision joint closed-loop target detection and a tracking system to ensure the precise landing of quadcopter in outdoor environments. The test result demonstrated that 75% average WPT efficiency have been achieved.

III. CPT SYSTEM OF UAVS

Capacitive power transfer is an important WPT technique based on electric field coupling [66], [67]. The auxiliary circuit consists of the power electronic period and the corresponding compensation structure. The capacitive coupling interface consists of two pairs of coupling plates, *e.g.* copper plate or aluminium plate. Two plates are used as a power transmitter on the primary side and the other two plates are used as a power receiver on the secondary side. There are also compensation network and rectifier connected to load at the secondary side. Fig. 3 shows a sample series compensation CPT equivalent circuit where V_p is the power source, L_P and L_S are the inductors in primary side and secondary side, respectively, C_1 and C_2 are the equivalent primary and secondary capacitances respectively, and C_M is the mutual capacitance between the interface, and R_L is the load.

For the WPT technology of UAVs, CPT has several advantages over IPT such that the CPT system uses the electric field as the energy transfer medium rather than the magnetic field, thus, the eddy-current loss is not considered [68]. In addition, there is no need for bulky and expensive magnetic materials, less attention is paid to EMI, and the power loss of the surrounding environment can be greatly reduced. Therefore, the need for EMI shielding during electronic circuit manufacturing can be reduced, thereby reducing the manufacturing weight and cost. Moreover, even though the efficiency of CPT system is sensitive to the location of transmitter and receiver plates.

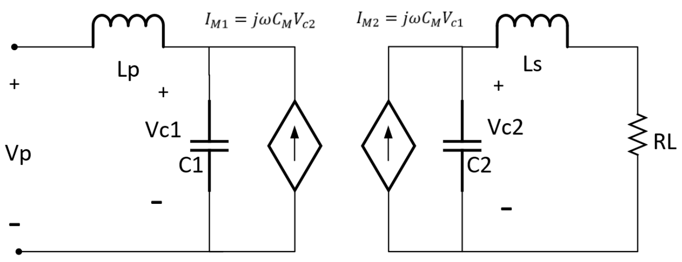
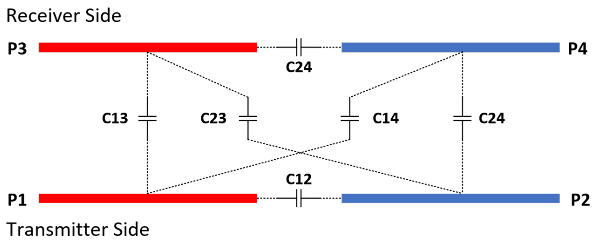


Fig. 3: Series Compensation Topology in CPT System

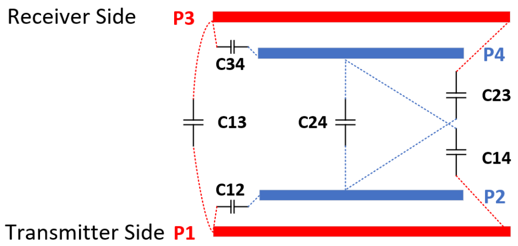
The CPT system can maintain 89.4% of the good alignment power under 300 mm misalignment, while the IPT system can reduce the power to 56% under 310 mm misalignment [69].

1) Coupling Interface:

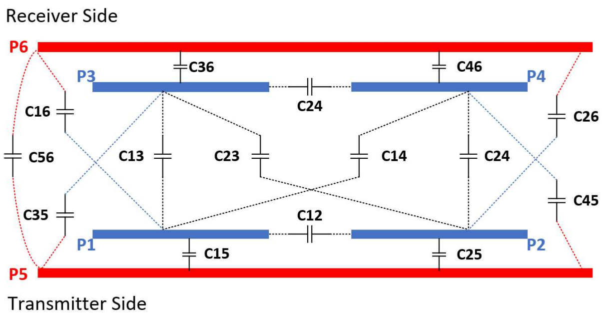
The coil configuration is multitudinous in IPT system, similarly, the capacitive coupling interface is various in CPT system, as shown in Fig. 4:



(a) Matrix (or lateral four-plate) coupling interface



(b) Row/Column (or vertical four-plate) coupling interface



(c) Six-plate coupling interface

Fig. 4: Coupling Capacitors in the Coupling Interface

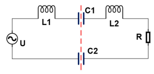
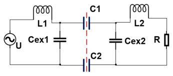
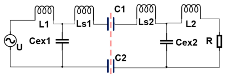
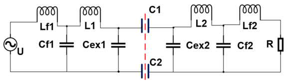
The matrix (or named Lateral four-plate) coupling interface which is the most common way to realise a capacitive coupler, as shown in Fig. 4a. $P1$ to $P4$ are located in the same horizontal position, where $P1$ and $P2$, $P3$ and $P4$ are placed at the transmitter and receiver respectively. A coupling capacitive is existed in each pair of the plate, resulting in a total of six capacitances. C_{13} and C_{24} are main coupling capacitances; C_{14} and C_{23} are cross-coupling capacitances; C_{12} and C_{34} are self-coupling capacitances [70], [71]. In general, when the plates are well arranged and the distance between the plates is short, the main coupler dominates the capacitance model. In this case, other couplers can be ignored in order to simplify the circuit analysis. But there is a situation where the plate is not aligned and the plate is relatively far away, the circuit analysis needs to be considered due to the cross coupling is large [72]–[74]. The matrix interface has high coupling coefficient and the voltage gain is nearly uniform. This six-capacitor model is more efficient and accurate.

Fig. 4b shows the row/column (or named vertical four-plate) coupling interface. These plate structures are designed to be symmetrical. P_1 and P_3 are larger than P_2 and P_4. Therefore, the coupling between P_1 and P_3 can not be eliminated by P_2 and P_4. The plate shape does not affect coupling, and usually C_{13} and C_{24} are much smaller than C_{12} and C_{34}. The cross-couplings of C_{14} and C_{23} are generated by the edge effect of $P_1 - P_4$ and $P_2 - P_3$, and they are therefore usually smaller than C_{12} and C_{34}. However, these problems cannot be ignored in practical circuits or circuit models requiring higher precision. The equivalent input capacitances of the plates from the primary and secondary side are mainly determined by C_{12} and C_{34}, and the values of C_{12} and C_{34} are determined by the distances of P_1 and P_2, P_3 and P_4 [75]–[77]. They have nothing to do with dislocation of the primary and secondary sides. Hence, the resonance of this coupler is not sensitive to the misalignment. However, the limitations of this coupler structure such as small mutual capacitance and the voltage stress are between the same-side plates. The cross-coupling capacitances C_{14} and C_{23} are increased, and the equivalent mutual capacitance is reduced. In the case of long distance transmission, the voltage stress between adjacent plates generally has more influence.

Fig. 4c shows that a six-plate coupling interface is placed between two large plates P_5 and P_6. The plate P_1-P_4 are active in transferring the power, and the plate P_5 and P_6 work as auxiliary plate for equivalent self-capacitance increasing and electric field shielding. In the CPT system, the active board and the compensation elements are directly connected, and the large plates are in a floating state. This structure can reduce the electric field emission to the surroundings when the P_5 and P_6 are connected to the ground, which means the two large plates work as the electric field shielding [78]. K. Doubleday *et al.* [79] proposed an optimisation methodology in a six-plate coupler CPT system. The structure has a 12 cm air-gap and uses in 6.78 MHz frequency. This system can transfer 589 W and achieve a power transfer density of 19.6 kW/m2 and efficiency of 88.2%. This coupler interface is not the best option for UAV application though it has advantage in EMI shielding, due to the complex structure will increase the UAV's weight.

2) Compensation Topology:

Table III: CPT Compensation Topologies

CPT Compensation Topology	Characteristics
 Series L Compensation Topology	Series L compensation topology is simplicity, and it can be applied in both low power and high-power applications. However, it lies in its requirements on inductance size and sensitivity with parameter variations, especially in long distance and high-power application.
 LC Compensation Topology	The main challenge in capacitive power transfer comes from the conflict between the extremely small coupling capacitances and the system power require. LC compensation topology can solve this challenge. LC compensation topology feasibility in long distance and high-power applications, and the resonances in this system is not sensitive to misalignment.
 LCL Compensation Topology	LCL compensation topology can flexibility to tune the system power through designing the inductance radio of L1 and Ls1, so as L2 and Ls2. However, the system power is reversely to coupling coefficient, and requires large value of series inductances in high power application.
 LCLC Compensation Topology	The advantage of LCLC compensation topology is that the system power can be regulated through circuit parameter design without affecting the coupling coefficient. However, the compensation topology is complexity, and the system cost and weight are increased.

There are several compensation topologies in CPT system. The most common compensation topology is series L compensation. The series L compensation topology is the reduce cost and weight implementation for UAV application, achieving a maximum efficiency of 80% [80]. The advantage of this topology is its simplicity, and it can be used in both high power and low power applications. However, the requirement on inductance size is sensitivity with parameter variations. To increase the coupling capacitance, the LC compensation topology was proposed. Hua Zhang *et al.* proposed a double-size LC compensation topology in electric aircraft charging application, both the input voltage and the load can varies in a wide range [81]. The advantage of LC compensation the resonance is not sensitive to the misalignment variations in the capacitive coupler, so it suitable for high power and long distance applications. But the system power transfer efficiency is inverse with the system power [82]. H. Zhang *et al.* proposed a double-sided LCL compensation topology for CPT system which can achieve an efficiency of 85.87% at 1.88kW output power with a 150mm air-gap distance [75]. F. Lu *et al.* proposed a double-sided LCLC compensation topology which can reach DC-DC efficiency of 90.8% at 2.4 kW output power [83]. Even though the efficiencies of above compensation topology above 90% is achieved with improved power transfer density. However, compared with the simple compensation topology (series L or LC compensation). The performance comparison of topologies shown in Table III.

3) Case Studies of UAVs CPT Charging:

Currently, the research on the CPT technology for UAVs charging is limited due to the fact that the CPT technology is relatively new compared with IPT technology. The CPT technology of the UAV application is more promising to realise high power, high efficiency, and low cost. There exist several challenges of UAV CPT charging that were summarised such as the high-power and high-frequency power converter design in the primary side, sufficient shielding with capacitive coupler structure design, and light-weight power converter design in the secondary side. Moreover, compared with other applications, the permittivity dielectrics between coupling interfaces play a important roly in UAV application. The high permittivity dielectrics uses the required mutual capacitance can be obtained in all configurations.

Vincent *et al.* [80] designed a 150*170 mm plate pair for UAVs CPT charging and provided a comparative simulation results of different configurations of capacitive plate interface and various air-gaps. Moreover, a detailed design methodology of UAVs CPT charging system was proposed such as a capacitive coupling structure selection and the compensation topology design, etc. Two coupling interface structures: row/column interface and matrix interface were selected to conduct the simulation. Simulation results show that the matrix arrangement has a higher mutual capacitance than the row/column structure of UAVs CPT charging [80]. Mostafa *et al.* [84] designed a CPT UAVs charging prototype that delivered 12W power. The design considerations are provided such as the operating frequency at 6.78 MHz to use a smaller area of the capacitive coupling, reducing the quality factor, and not objecting with the frequency of other devices [84], [85]. Zhang *et al.* [81] proposed a high power CPT charging system for electric aircraft. A modular multi-level converter is used in the prototype. The coupler uses 200*150 mm 2*2 matrix metal plates, and the plates are placed on the glass insulation layer. The experimental results show that the proposed CPT system achieves 1.53 kW power transfer with 92.1% dc-dc efficiency [81].

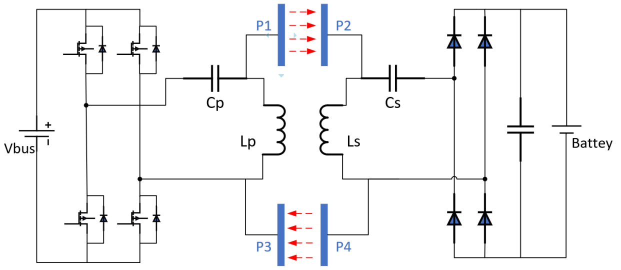
4) Safety Issues: There are some important safety problems in CPT system, such as high voltage stress between plates and strong electric field on the surrounding environment. When high power transmission is realized, the plate voltage can be raised to kV level, which is potentially dangerous to users. Therefore, the surface of capacitive couplers must have reliable insulation measures. B. Geemph *et al.* proposed a ceramic coating, which has the characteristics of durability, high dielectric constant, high dielectric strength and easy application, and can be effectively used for electrical isolation [86].

IV. HPT SYSTEM OF UAVS

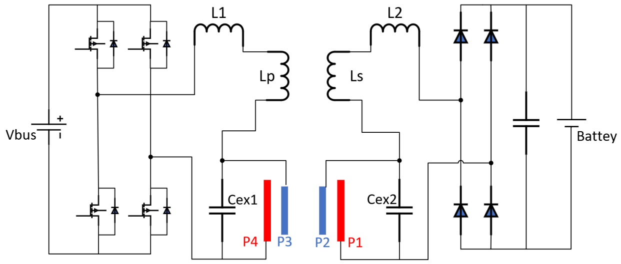
Hybrid wireless power transfer (HPT) employs both magnetic and electric fields to transmit the power across air-gap distance at the resonant frequency [87]. Through the previous summary, we can see the transfer efficiency and voltage in the IPT system can be affected by the size of the transmitter and receiver coils. In general, a larger receiver coil will reach a higher transfer efficiency. But the weight of the coil will increase significantly. It is not a good choice especially charging for the weight sensitive UAVs. The advantages of the CPT system is lighter weight and low-cost metal plates. However, the CPT system is limited to small power transfer and short distance. Moreover, the efficiency of the CPT system is sensitive to the location of the transmitter and the receiver plates. This requires high accuracy when the drone lands on the charger. In light of this, the hybrid wireless charging which can combine the advantages of IPT and CPT technology is useful for UAVs charging. The summary of HPT system could gain the competitive advantages over IPT and CPT as follows [88]:

- Supporting higher power capacity and density for wireless charging, improve the charging efficiency for UAVs application;
- Utilizing resources more efficiently in both electronic components and electromagnetic fields; Compacting the system design, especially in the antenna size and the number of electronic components used;
- More tolerance in misalignment cases;
- Reducing the EMI problem, particularly electromagnetic for airborne equipment;

1) Topology of HPT System:



(a) Hybrid system with matrix interface CPT



(b) Hybrid system with row&column interface CPT

Fig. 5: Topology of the HPT System

The hybrid IPT and CPT system have been proposed in recent years [89]–[92], as shown in Fig. 5. Depending on the difference of CPT structures, Fig. 5a displays a matrix CPT hybrid system. Each of the four metal plates is connected to a coil in an IPT coupler. Two capacitors C_p and C_s are series resonant connect to the primary and secondary side in the hybrid system. L_P and L_S respectively represent the self-inductance of the primary and secondary side coil. The SS compensation is used to simplify the system analysis. A high frequency inverter is used on the primary side for DC/AC converter, and the compensation topology is provided according to the designed switching frequency. On the secondary side, the rectifier is used to convert the AC power supply to the dc power supply under the load [93].

The row/column CPT hybrid system is shown in Fig. 5b. The IPT system and the CPT system are independently, and four plates form two transmission channels in CPT system. L_1, C_{ex1} and L_2, C_{ex2} are respectively placed on the primary side and the secondary side to adjust the transmission power and system resonance [94], [95]. In the primary side use full bridge inverter to provide AC excitation for compensating network, in the secondary side use full bridge rectifier to provide DC output source. The circuit compensation topology is similar to the double LC compensation topology except for that inductive coupling coils L_P and L_S are used between the compensation inductor L_1 and L_2 and capacitive coupler both the primary and secondary side.

2) Coupler Design of HPT:

Similar to the IPT and CPT technologies, HPT technology has various coupler structures depending the different application and requirement.

Li *et al.* [96] proposed a peer-to-peer WPT systems incorporate a parallel transmission approach of power and data. The inductive coils on the top and capacitive plates are outermost layer. The system transfers data and power in a capacitive and inductive approach respectively. The coupler structure is shown as Fig. 6a. In the proposed system, a 40 W prototype is established associated with a 230 kbps transferred data speed. Comprehensive test results have shown that data transfer channel almost does not affect on the power transfer. The proposed method is suitable for UAV applications due to the strong flexibility.

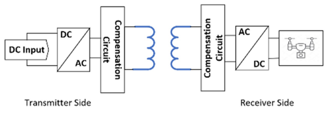
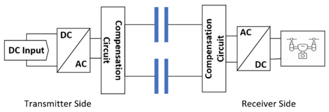
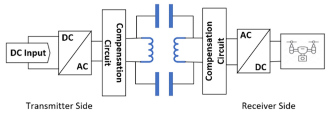
A novel hybrid coupler in Fig. 6b was proposed and designed to keep a stable open-loop gain when coupling capacitance varies [97], [98]. The hybrid coupler is composed of two separable PCB boards, namely the primary pad and secondary pad. Each pad includes two capacitor plates and a PCB based coil in the middle. Through evaluating the gain characteristics of the hybrid coupler to make sure that the output voltage and power meets the design requirement under different conditions, then the whole charging system can be designed. Finally the proposed coupler is verified with a 40 W, 6.78 MHz experimental prototype.

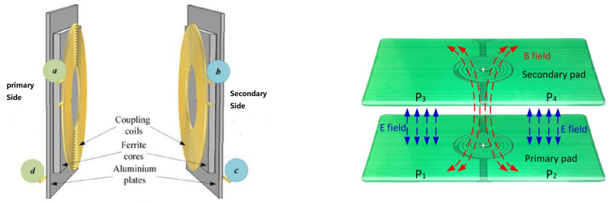
Zhou *et al.* [99] has proposed a method to WPT across a metal barrier. In the proposed system structure as shown in Fig. 6c, two transmitting plates and a metal barrier are designed at the primary side, the current flow in the metal barrier, which generates a magnetic field for transferring power via an inductive coil at the secondary side. On the secondary side, a coil upon the barrier is connected up to the load and a secondary compensating circuit. The proposed design can get high output power (the experimental results have demonstrated that over 11W), however, it is more sensitive to the variation of the distance and positioning of the receiving coil.

3) Compensation Topologies:

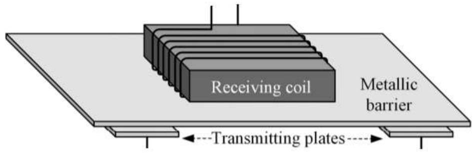
The S-S compensation topology is also the common topology in hybrid system. The four metal plates of CPT are connected to the coils of the IPT coupler separately, and two capacitors are used to resonant the hybrid system. The advantage of S-S compensation to simplify the system design [93]. F. Lu *et al.* proposed the LC compensation topology which compacts the system design to get high power transfer efficiency [89]. The LC compensation topology of the HPT system is similar to the LCL compensation topology of the CPT system, because the inductor coil of the IPT can replace the L in the LCL compensation. However, the maximum power output and power transfer efficiency of HPT are higher than those of CPT [73]. The power ratio of the IPT and CPT is the challenge in HPT system design. Moreover, the resonant frequency selection is important for HPT system due to the IPT and CPT will works in different frequency levels. Z. Liu *et*

Table IV: Comparison summary of IPT, CPT and HPT system for UAV application

Name	IPT Technology	CPT Technology	HPT Technology
System Structure			
Frequency Range	10's kHz to MHz	1MHz to 10's MHz	Adjustable (Depend on the requirement)
Air Gap Distance	<500mm	<30mm	<100mm
Compensation Topology	Series-Series compensation topology; Series-Parallel compensation topology;	Series L compensation topology; LC compensation topology;	Series-Series compensation topology; LC compensation topology;
Normal Power Level	10's to 100's W	10's W	10's W-100's W
Max Power Efficiency	93%	90%	>90%
Technical Analysis	Advantage: Mature technology Disadvantage: EMI Problem for UAVs airborne devices and communication	Advantage: No EMI problem, light-weight for UAVs application; Disadvantage: Power level and distance lower than other technology	Advantage: Supporting higher power capacity and density, compacting the system design; Disadvantage: New technology
Research Challenges	1: Under the premise of high power and efficiency, light-weight design including the coupler coil、system circuit aspect; 2: EMI shielding	1: Coupler structure design 2: Increase the power transfer efficiency	1: Coupler structure design 2: The power radio/ power distribution of IPT and CPT system 3: The frequency selection of IPT and CPT



(a) Parallel hybrid coupler [96] (b) PCB hybrid coupler [97], [98]



(c) Metal barrier hybrid coupler [99]

Fig. 6: Coupler Structure of the HPT System

al. proposed a selective frequency hybrid compensation which can supply the LC compensation and LCL compensation at different frequency value [100].

V. DISCUSSION AND INSIGHTS

The comparative summary of IPT, CPT and Hybrid WPT (HPT) for UAV application in characteristics, technical analysis, and research challenges is shown in Table IV. There are precise requirements on the landing position of the UAVs due to that the misalignment will reduce the power transfer efficiency rapidly. The resonant coupler design and the control algorithm development are investigated to solve the misalignment problems. Both IPT wireless UAVs charging and CPT wireless UAVs charging technologies have their own advantages and disadvantages. The main research issues of the IPT wireless UAVs charging are the coils which will add the UAVs weight and the EMI problem. Existing researches primarily focus on coil design, system control and EMI reduction, *etc.*. The CPT wireless UAVs charging can solve the EMI problems and couplers will add almost no weight to the UAVs, but the power level and transfer efficiency are lower. To combine the merits of both techniques, the hybrid IPT/CPT WPT technology has been proposed. The hybrid WPT technology is suitable for the wireless UAVs charging, whereas it has not been widely used in UAVs yet. The research challenges of HPT technology such as 1) the power radio/ power distribution of IPT and CPT system; 2) the frequency selection is important due to the IPT and CPT works at different frequency levels.

The system design challenges of near-field UAVs charging include:

- High power transfer efficiency system
- High misalignment tolerance
- light-weight circuit design, particularly on secondary side
- low Electro-Magnetic Influence (EMI) problem, particularly in IPT technique

Some recent researches of near-field wireless UAV charging technology have been summarised as shown in Table V. The future developments of wireless UAVs charging could mainly be expected from four key aspects, *e.g.* acceleration, mobilization, optimization and generalization, detailed as follows:

- Acceleration: developing high power fast WPT system for UAVs, enabling the fast charging for UAVs in time sensitive applications.

Table V: The summary of several recent works

References	Drone Type	Technique	System Topology	Coupler Size	Frequency	Air Gap	Charge Power	Transfer Efficiency	**Characteristics** Advantage(A);Disadvantage(D)
[40]	N/A	IPT	N/A	445*460 (mm)TX	85kHz	-	450W	>78%	A: large battery available D:Low PTE
[43]	DJI F550	IPT	S-P	400*150 (mm)TX	200kHz	100mm	64W	>85%	A: High level tolerance of misalignment receiver coil on the landing leg that unchanged the payload and the vision
[46]	DJI MG-1	IPT	S-S	140*50 (mm)RX	100kHz	100-500mm	500W	90.8%	A: High electric energy transmission for misalignment D: Increase the weight of pick-up side
[51]	DJI F550	IPT	S-P	Diameter 400(mm) TX	300kHz	50mm	24W	89%	A: light-weight of pick-up side High tolerance of landing D: No consider the EMI
[55]	N/A	IPT	S-S	400*400 (mm)TX	1MHz	100mm	10W	93%	A: High efficiency D: Low power level EMI problem of UAV's devices
[63]	N/A	IPT	S-S	N/A	60kHz	-	150W	72%	A: Effectively solve the EMI problem D: High sensitive of UAV landing
[80]	DJI F550	CPT	LC	150*170 (mm)	1-6 MHz	20mm	72 W	90%	A: Details of coupling interface design D: No implementation prototype
[84]	N/A	CPT	Series-L	300*300 (mm)	6.78 MHz	-	12W	50%	A: Small circuit design in pick-up side D: Capacitive interface affect the vision
[81]	Aircraft	CPT	LC	200*150 (mm)	5MHz	-	1.53 kW	92.1%	A: WPT for electric aircraft D: No consider the cost
[96]	N/A	HPT	P-S	IPT(mm): Diameter 45 CPT(mm) 100*80	CPT: 10MHz IPT: 40kHz	20-50mm	-	CPT: 65-80% IPT: 77-85%	A: Parallel transmit Data and Power D: Big weight of the devices
[97], [98]	N/A	HPT	S-S	IPT(mm) N/A CPT(mm) 330*220	IPT: 6.78MHz CPT: 5-10MHz	50mm	40 W	IPT: 64.93% CPT: 75.16%	A: Novelty Hybrid charging structure D: No consider EMI

- Mobilization: enabling the mobility in the charging process, and developing potable and mobile charging platforms such as electric vehicles and UAVs itself.
- Optimization: improving the charging efficiency of WPT for UAV, extending the charging range, combining the trade off of hybrid IPT/CPT *etc.*.
- Generalization: activating the general WPT between UAVs and other energy storage agents, such as the Electric vehicles (EVs)-UAVs charging system and power transfer among UAVs.

The technical breakthrough of aforementioned four aspects may endow strong flexibility and availability for UAVs to tackle with more challenging applications. UAVs are promising to be equipped by a more flexible way in gaining energy supply by developing more powerful and specific WPT technologies.

VI. CONCLUSIONS

In recent years, UAVs have become technologically sophisticated due to the significant advances in robotics, sensing and communication technologies, and artificial intelligence. The UAVs can not only enrich and extend the human capabilities but also replace human operations for dangerous tasks, such as rescue (fire rescue and sea rescue), detection in special circumstances. One of the most significant technical challenges is its limited flight time. In order to tackle this challenge, the wireless charging is a promising technology. The near-field wireless UAVs charging technologies mainly include IPT technology and CPT technology. The key factors of technology development focus on high efficiency, light-wight pike-up devices, and high tolerance of landing. Hybrid WPT technology combines the advantages of the IPT technology and the CPT technology which is suitable for UAVs application. This paper presents a comprehensive review of the state-of-the-art researches on the near-field wireless power transfer technology for UAVs charging, covering the characteristics of different WPT techniques, design issues, and case studies. Future work will be addressing the four key technology development in terms of acceleration, mobilization, optimization and generalization.

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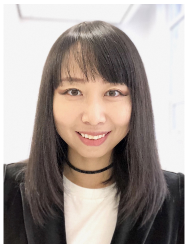

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