A 100 W 6.78 MHz Inductive Power Transfer System for Drones

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Abstract—This paper reports on the design and development of a wireless charging solution for a DJI Matrice 100 quadcopter drone. The system is based on a high frequency inductive power transfer system built with lightweight copper pipe air-core coils at both ends and lightweight electronics at the receive side. The developed system is capable of delivering power to the drone at the same rate as the original wired charger (100 W) when landed at any position on the charging pad, regardless of the lateral misalignment or angular orientation. The charging pad is circular with a one-metre diameter, therefore allowing for a lateral misalignment of up to 25 cm. The system has an average mains-to-battery efficiency of 70 % and enables the drone missions to be completely autonomous as it eliminates the need for human interference for battery recharging or swapping.

I. INTRODUCTION

Rotary-wing unmanned aerial vehicles (UAV) are used in a variety of monitoring, search-and-rescue and surveillance operations [1]. These drones are being equipped with an increasing number of features such as video recording, GPS tracking, etc. Many of the added features facilitate the autonomous operation of drones, reducing direct human intervention and interaction. However, a limitation of such drones is that their battery only supports a relatively short flight time, with the duration significantly reduced as the payload increases. Consequently, a human is still required to charge or swap the batteries so that the drone can complete a series of tasks or operations over extended periods.

In order to enable complete autonomy of drone operations, wireless charging is necessary in order to remove the recurrent interaction between the human and the drone, thereby simplifying the charging process for autonomous drones. However, using an inductive powering system that adheres to the commonly-used Qi wireless charging standard would require precise alignment between the wireless power transmitter and receiver in order to deliver enough power efficiently. A mechanical system to align the coils to optimise wireless charging, as showcased in [2], could address this issue, but at a cost of implementing an additional system on top of the wireless charging system. Alternatively, multi-MHz IPT systems allow for a higher tolerance to misalignment [3], [4]. In [5], a MHz inductive power transfer (IPT) system was developed to power a Hubsan H107L X4 drone with its battery removed, where the benefits of operating an IPT system in the multi-MHz frequency range using lightweight ferrite-less copper coils and load-independent soft-switching power converters (e.g., [6]) with wide-bandgap semiconductor devices were highlighted. However, such small and lightweight drones have limited battery capacity and do not have the ability to carry any significant payload, so they are not suitable for many industrial applications.

This work presents a wireless charging solution for the DJI Matrice 100, a development drone platform that can be used in a wide range of applications and has a more practical payload of 1 kg (Fig. 1). This system has been designed to overcome several technical challenges, such as power electronics to cope with a highly variable coupling factor due to the limited landing precision of the drone and a shielding method to eliminate the effects of the transmit-side inverter detuning when placed in different electromagnetic environments. As a result, the DJI Matrice 100 drone can be charged at a rate of 100 W over a distance of 14 cm with up to 25 cm of misalignment tolerance.

II. SYSTEM DESIGN

The drone selected for this work is the DJI Matrice 100. It is supplied with a 22.2 V, 4500 mAh rechargeable LiPo battery (model number TB47D). As the battery charger (model number A14-100P1A) has a maximum power output of 100 W, the wireless power transfer system will be designed to charge the battery at the same rate.

Fig. 2 shows a block diagram of the drone wireless charging system. The ‘Mains-rectifier’ and ‘PFC / DC-DC converter’
blocks refer to the power conversion from the ac mains to a dc voltage. The ‘Inverter’ block comprises the load-independent Class EF inverter used to drive the transmit coil with a high frequency current to generate an ac magnetic field. The ‘IPT-link’ block represents the power transferred from the transmit coil inside an enclosure on the ground to the receive coil mounted on the drone through the inductive link, where coupling $k$ is a variable. In terms of receive electronics on the drone, the ‘IPT rectifier’ block is a full-wave current-driven Class D rectifier and the ‘dc-dc converter’ block consists of a buck converter with a wide input voltage range to cope with variable coupling and an output voltage level suitable for charging the on-board drone battery.

### A. Coils, IPT link and shielding

The transmit coil is a 2-turn square coil made of 8 mm copper pipe, with an inner and outer length of 350 mm and 400 mm, respectively. The receive coil on the drone is a single-turn circular coil (also made of 8 mm copper pipe) with a diameter of 400 mm. The vertical distance between the transmit coil and the receive coil is 14 cm. As there is a one-metre diameter circular landing pad on top of the transmit coil, the maximum lateral misalignment between the receive coil and the transmit coil is 25 cm.

Electromagnetic simulations in CST Microwave Studio were performed to derive the coil and link properties. The receiver coil has a simulated inductance of 1.13 $\mu$H and a Q factor of 1143. Overall configuration is shown in Fig. 3. In the presence of the aluminium shield, the transmitting coil’s inductance and Q factor are 3.63 $\mu$H and 1487, respectively. The coupling factor is 16.7% when perfectly aligned and 5.1% at the maximum lateral misalignment (in the worst case direction) of 25 cm. The transmit coil and the aluminium shield are shown in Fig. 5.

Using the coils’ impedance and the coupling factor at maximum lateral misalignment (i.e. minimum coupling) in the presence of the aluminium shield and assuming series tuning at the receive side, the link parameters corresponding to 100 W received power when the optimal load is used for maximising link efficiency are given in Table I (where $k$ is the coupling factor, $\eta_{\text{link}}$ is the link efficiency, $I_1$ and $I_2$ are the primary and secondary coil current amplitudes, $C_S$ is the secondary series tuning capacitance, $R_L$ is the optimal load resistance and $R_{\text{refl}}$ is reflected resistance seen at the transmit side).

### TABLE I

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k$</td>
<td>5.1%</td>
</tr>
<tr>
<td>$\eta_{\text{link}}$</td>
<td>97%</td>
</tr>
<tr>
<td>$I_1$</td>
<td>5.45 A</td>
</tr>
<tr>
<td>$I_2$</td>
<td>8.46 A</td>
</tr>
<tr>
<td>$C_S$</td>
<td>489 pF</td>
</tr>
<tr>
<td>$R_L$</td>
<td>2.79 $\Omega$</td>
</tr>
<tr>
<td>$R_{\text{refl}}$</td>
<td>6.83 $\Omega$</td>
</tr>
</tbody>
</table>

### B. The Wireless Power Transmitter

At the transmit side, a load-independent Class EF inverter (Fig. 4) was used to drive the coil at a frequency of 6.78 MHz. The design was based on the guidelines in [6], and the component values of the circuit are shown in Table II. The transistor implemented in this inverter was a 30 A 650 V gallium nitride (GaN) transistor (GS66508B) from GaN Systems. One of the key advantages of this topology is that the inverter can maintain zero voltage switching (ZVS) regardless of the reflected resistive load from the receive side, so that the load and coupling variations between the transmit and receive coils do not affect the soft-switching operation of the inverter. The construction of the transmitter is shown in Fig. 5.

Finally, as shown in Fig. 6, a one-metre diameter acrylic landing pad was placed on top of the IPT transmitter, where the biggest challenge lies in the ability of the system to operate efficiently independent of the drone’s position on the landing pad. The separation of the coils and the size of the landing
pad dictate the range of coupling for the drone to land and 
recharge. As this system relies on variable coupling, it was 
designed considering the spatial distribution of coupling as 
in [7] from simulations but also from measurements.

C. The Wireless Power Receiver

The receive side circuitry consists of a full-wave Class D 
rectifier and a dc-dc converter (based on LTC3895) to provide 
a constant output voltage to charge the TB47D battery of 
the drone. Silicon carbide (SiC) Schottky diodes (Wolfspeed 
C3D04060E) were implemented in the rectifier, as SiC diodes 
in general have a higher breakdown voltage tolerance and lower 
junction capacitance than silicon Schottky diodes. The 
block diagram of the receiver is shown in Fig. 8, and the 
developed system is shown in Fig. 7.

As a final power conversion stage the battery charger for 
the drone’s battery is required to have a wide input voltage 
range since the induced voltage on the receive coil depends on 
coupling, i.e. on the landing position of the drone. The charger 
should also be capable of handling 100 W to charge the battery 
within the coupling range. Based on these specifications, an 
LTC3895 evaluation board was chosen as the last power 
conversion stage of the system.

III. Field Testing

A crucial feature of using high frequency IPT systems for 
wireless charging of autonomous drones is that these can be 
designed for a wide range of misalignment and independent of 
angular orientation [7]. Thus, the drones to be charged do 
not require a millimetre-precise landing system. In this section 
we report on the final testing of the system in the laboratory 
and how it was later deployed in a real-world scenario.
A. System Testing in the Laboratory

Using a WT332E and a WT310 digital power meter by Yokogawa we measured the input and output power to determine the average efficiency of the IPT system as the alignment of the coils change. The proposed IPT system was tested to be capable of delivering 100 W to the drone either at the centre or at any edge of the charging pad without the angular orientation of the drone having any impact on the performance (Fig. 6). The system was tested by performing a full charge of the battery several times at different alignments and the results show that the average mains-to-battery efficiency was 70 % (It changes slightly with the alignment of the coils and the state of charge of the battery). Interestingly, as the drone was moved further from the centre, the output power increased slightly (around 10 W maximum) due to the control configuration of the dc-dc converter after the rectifier, and the efficiency remained fairly constant (less than a 1 % change) as the receive coil position changed. Given the positive outcome of the laboratory tests, the system was then trialled in a real-case scenario.

B. Deployment of the Wirelessly Charged Drone in a Real-case Scenario

While the developed system works as expected in the laboratory environment, the robustness of the system still needed to be evaluated as a real application. This was also an opportunity to test if the 6.78 MHz IPT system interferes with the operation of the drone itself when it approaches the charging pad.

A flight-land-charge test was demonstrated on the Halcyon–Thales’s autonomous surface vessel. The challenges involve connecting the system from a power outlet of the ship instead of a controlled AC source (we used an AC6802A AC supply by Keysight) and dealing with environmental conditions, e.g. vibrations from the engine of the vessel, motion due to waves and manoeuvring, wind, humidity, etc. IPT was performed in various scenarios including whilst driving the vessel at a constant speed. In these tests we could only verify that the battery was being charged by the indicators on the drone and the controller, and we included an AC power meter in the power supply to make sure that the input power of the system was congruent with that measured in the laboratory.

The drone landed on the charging pad several times (9) and was charged successfully. There was no sign of interference during the entire operation.

IV. Conclusions

This paper presented the design and development of a 100 W IPT charging system for autonomous drones which was deployed in a real-case scenario. The designed system was able to tolerate a wide range of misalignment and achieved an average end-to-end efficiency of 70 %.

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