Wireless Charging System Integrated in a Small Unmanned Aerial Vehicle (UAV) with High Tolerance to Planar Coil Misalignment

T. Campi[1], S. Cruciani[1], F. Maradei[2] and M. Feliziani[1]

[1]Department of Industrial and Information Engineering and Economics, University of L'Aquila, L'Aquila, Italy
[2]Department of Astronautics, Electrical and Energetics Engineering, Sapienza University of Rome , Rome, Italy

Abstract— **An innovative coil configuration for inductively-based wireless power transfer (WPT) technology is presented to recharge the battery of a compact unmanned aerial vehicle (UAV) (i.e., a remotely controlled drone). To improve the tolerance of the WPT system to coil misalignment caused by imperfect landing, a large primary coil is proposed in combination with a single turn, secondary coil. The on-board secondary coil is integrated in a part of the drone used as protection of the propellers. The single turn configuration of the secondary coil is efficient from an electrical point of view and very convenient as the additional weight installed on-board the drone is very limited.**

Keywords— Battery charging, drone, magnetic resonant coupling, wireless power transfer (WPT), unmanned aerial vehicle (UAV).

I. INTRODUCTION

The use of small size unmanned aerial vehicle (UAV) systems is rapidly spreading in various application areas. In the future, drones will be widely used for continuative and autonomous missions, for example in agriculture and surveillance applications. The main limitations for the diffusion of the drones for continuous flight are basically two: regulatory limitations, and the lack of robust and automatic systems for battery charging or replacing. From the regulatory point of view, the drones with a weight under a specific limit can be used with fewer restrictions because they are considered harmless. However, drones with a take-off weight below 300g are mostly classified as 'inoffensive UAV' [1]. The other important limitation is the reduced autonomy of the battery.

To overcome this last issue it is necessary to create dedicated base stations where the drone can land to automatically recharge its battery. Nowadays, after drone landing, an intervention of a human operator is requested to recharge or replace the battery. Several solutions have been proposed to realize autonomous charging pads using electrical contacts or wireless. The first solution is more efficient, but the presence of the electric contacts makes the charging system fragile in case of bad weather conditions. The second solution is mainly based on magnetic resonant coupling [2]-[4]. Several works have been proposed for drone charging ground stations based on inductive coupling [5]-[10]. However, in order to consolidate the use of WPT for drone battery recharging, there are still some critical issues to be addressed, such as the need of a good tolerance to coil misalignments in case of imperfect landing, and the weight minimization of the WPT onboard components. To this aim two different solutions have been proposed: a movable primary coil or an array of primary coils. The first solution has the advantage that the transmitting and receiving coils are always well coupled together, on the other side the mechanical system used to move the primary coil can introduce complexity and reduce system reliability [6]. The second solution is more robust but it requires a detection system to power the primary coil in correspondence of the landed drone position [7]-[8]. In both solutions the on-board coil is a separate component that must be mounted on the drone, increasing its weight and reducing the payload. This could be a big problem especially for small drones that must respect a maximum takeoff weight limit. To overcome the inconveniences of the two methods, an innovative solution is here proposed. It is based on the use of a large primary coil and a single turn secondary coil integrated in a pre-existent part of the drone.

II. SYSTEM CONFIGURATION

The goal of the proposed configuration is to maximize the area covered by the wireless charging system reducing the weight of on-board components. To this aim, the main idea is to realize a large primary coil placed on the ground pad where the drone automatically lands when the battery reaches a low level. The light secondary coil is integrated in the drone structure, as shown in Fig. 1. The use of a large primary coil, widely used in WPT biomedical applications, permits to magnetize a wide area where the secondary coil, without fixed position, can be located [11]. Moreover, in drone WPT applications, it is necessary to transfer a big amount of power to the load with high efficiency and, at the same time, to reduce the weight of the on-board secondary coil as much as possible. The resonant frequency is here fixed to 300 kHz as suggested by the Qi standard for medium power applications [12]. This frequency permits to obtain a good tradeoff between the transferred power and the total efficiency. Nevertheless a higher frequency would permit an increase of the coil-to-coil efficiency, its use is not practicable due to enhanced costs and complexity of the electronic systems both on the ground station and on-board the drone. The WPT system design is presented in the following.

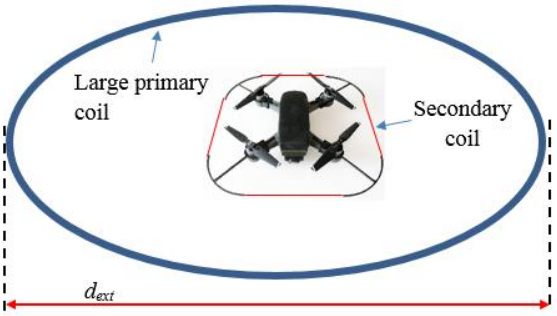


Fig. 1. Proposed WPT configuration.

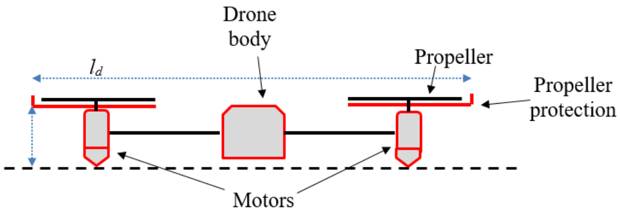


Fig. 2. Sketch of the considered drone.

a) System specification

The considered WPT system is aimed to recharge the battery of a sub-300 g category drone shown in Fig. 2. The first step is to define the electro-geometrical constraints of the on-board coil. This drone has maximum width dimension $l_d = 20$ cm and the total weight must be limited to 300 g. The precision of the landing procedure depends on the autopilot, but generally a tolerance of $l_t = \pm 40$ cm is enough to ensure the correct landing on the ground pad. The drone battery is characterized by a nominal voltage $V_{bat} = 3.7$ V, and a variable capacity $Q_{bat} = 1000 - 3000$ mAh. For the highest value of the battery capacity (i.e., $Q_{max} = 3000$ mAh), the power required to recharge the battery is $P_L = 12$ W in case of charging in 1 hour, and $P_L = 24$ W for ultrafast recharging in 30 min. Thus, the design specifications of the charging area and the electrical requirements are:

- Circular pad with diameter $d_{ext} = 80$ cm.
- Transferred power $P_L = 24$ W.

b) WPT equivalent circuit

The WPT technology allows transferring electrical energy by means of magnetic resonant coupling between two coils. A simplified electrical circuit of a WPT system is reported in Fig. 3. The two coupled coils are characterized by self-inductances L_1 and L_2, mutual inductance M and self-resistances R_1 and R_2 that model the losses in the coils [13]. The coupling factor k is given by:

$$k = \frac{M}{\sqrt{L_1 L_2}} \qquad (1)$$

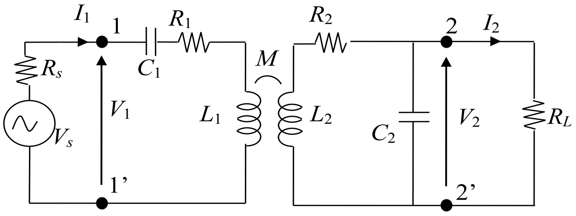


Fig. 3. Equivalent circuit of the WPT system with SP compensation.

The resonance condition is obtained by using compensation network both on the primary and secondary side. Compensation network is mainly realized with capacitors that can be connected in several ways [14]. The most widely used compensations topologies are the series-series (SS) and the series parallel (SP). The WPT equivalent circuit is fed by a sinusoidal voltage source V_s while the load is modeled as a simple resistor R_L.

The parameters of the coils in terms of self and mutual inductances (L_1, L_2, M) and resistances (R_1, R_2) are numerically calculated at the frequency of interest solving the magneto quasi-static (MQS) field equations by a finite element method (FEM) [12]. Then, the values of the compensation capacitors (C_1, C_2) are calculated accordingly to [14] for the selected compensation topology.

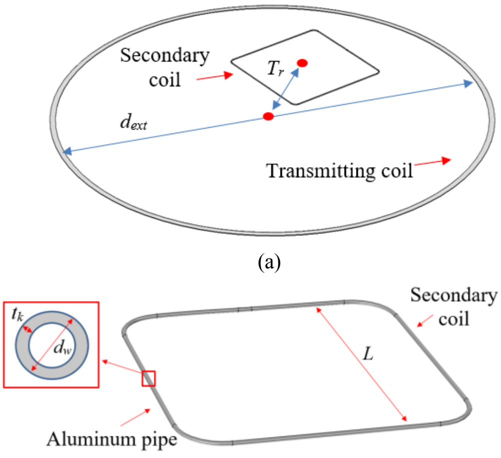
By the analysis of the equivalent circuit, the electrical performances of the system are evaluated in terms of efficiency η and transferred real power P_L to the load. The efficiency is defined as $\eta = P_L / P_1$ where P_1 is the real power provided at the input port 1-1' of the equivalent circuit.

III. SYSTEM DESIGN

a) On-board coil design

In order to maximize the efficiency and the transferred power at any point in the ground pad, the optimization of the coils and the selection of an adequate compensation topology are very important factors. For the secondary single turn coil it is necessary to maximize its area. To this aim, in the proposed solution the protections of the propellers are substituted with a metal loop coinciding with the secondary coil. Using this configuration we obtain a large single turn secondary coil without adding new components and without any significant weight increase. Moreover, this kind of drones uses the motors as landing support, thus the vertical distance h_d of the propeller protections from the horizontal ground pad is very small ($h_d = 5$ cm) giving rise to a good coupling between the coils.

There are mainly two solutions for the realization of the receiving coil: the use of a copper Litz wire placed over the propellers or remove the plastic propellers protection and replace them with an aluminum pipe. The use of the Litz wire permits to reduce the AC resistance of the coil but it has poor mechanical properties and significant weight. The use of an aluminum pipe permits to have both good mechanical properties and low AC resistance. Thus, it is convenient to adopt an aluminum pipe for the secondary coil wire which also acts as propellers protection. Considering a drone with external dimension $l_d = 20$ cm, the aluminum receiving coil has a square shape with rounded corners of fillet radius $r_f = 2$ cm and side length $l_c = 20$ cm. The thickness of the pipe is chosen to mitigate the skin effect losses in the coil. At the considered frequency $f = 300$ kHz, the skin depth is $\delta = 0.15$ mm, so an aluminum tube of thickness $t_k = 0.15$ mm is selected as the wire of the 1-turn secondary coil, as shown in Fig. 4. However, if you want to improve mechanical strength, a larger pipe thickness t_k can be used. A FEM parametric analysis is performed varying the external diameter d_w of the tube to calculate the self-resistance and self-inductance of the coil. The self-resistance R_2 and the weight of the coil are reported in Fig. 5 varying the aluminum pipe external diameter d_w. On the other side the variation of d_w has a negligible effect on the self-inductance L_2 and the value is approximately $L_2 = 0.7$ µH in all cases. From the obtained results it is possible to choose an optimal dimension of the pipe that meets the requirements limiting both the weight and the resistance. For the considered drone, a maximum admissible coil weight of 20 g is fixed, thus the coil wire has $d_w = 1.6$ mm and resistance $R_2 = 15$ mΩ.



(a)

(b)

Fig. 4. Configuration of the proposed WPT coil system with lateral misalignment T_r (a). Configuration of the on-board secondary coil (b).

b) Base station coil design

The optimization of the transmitting coil placed on the ground station is important to maximize the WPT performances. The external dimension of the primary coil is limited by the size of the ground station. This last is strictly related to the precision of the landing system which has a tolerance $l_t = 0.4$ m. Therefore, for this kind of application, the only geometrical parameter that can vary is the lateral alignment, as the vertical distance between the drone and the ground pad is fixed and the inclination between the primary and secondary coils axes is equal to zero.

The primary coil is designed with a circular shape, however, other shape could be considered based on the specific usage scenario. The external diameter of the primary coil is set to $d_{ext} = 0.4$ m. The number of turns N_1 and the capacitive compensation topology are optimized to maximize the WPT performances. The primary coil is made of a copper Litz wire composed by 840 strands of AVG 41 wires to reduce the AC losses at the considered frequency.

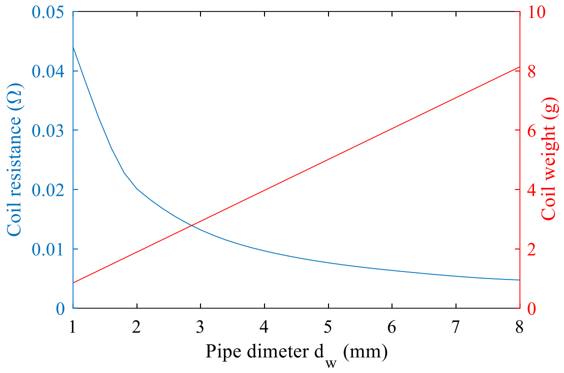


Fig. 5. Self-resistance and weight of the on-board secondary coil varying the diameter d_W of the aluminum pipe.

The per-unit-length AC resistance of the Litz wire is $R_m = 5$ mΩ/m. The self-resistance of the primary coil and the mutual inductance are calculated varying the number of turns N_1 of the primary coil in the range 1 – 10, as shown in Fig. 6. The mutual inductance is calculated considering the secondary coil perfectly aligned, i.e., placed in the center of the transmitting coil.

Finally, a map of the magnetic field on the plane parallel to the primary coil at height $h = 5$ cm is shown in Fig. 7 considering as excitation a single turn primary coil with unitary current. The map shows the validity of the proposed configuration with a quite uniform magnetic field in all the area inside the primary coil, where the secondary coil can be located. However, a more complex design of the primary coil can be considered to improve the field uniformity [7].

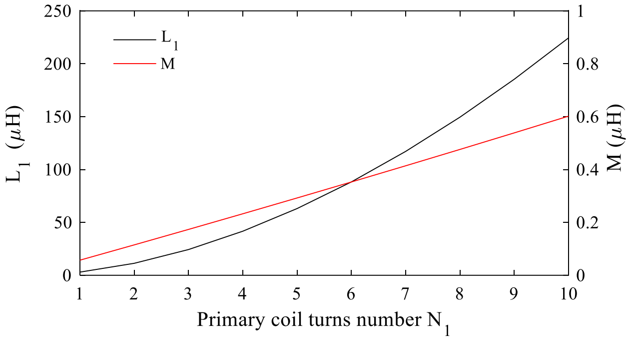


Fig. 6. Self-resistance and mutual inductance of the primary coil varying the number of turns N_1.

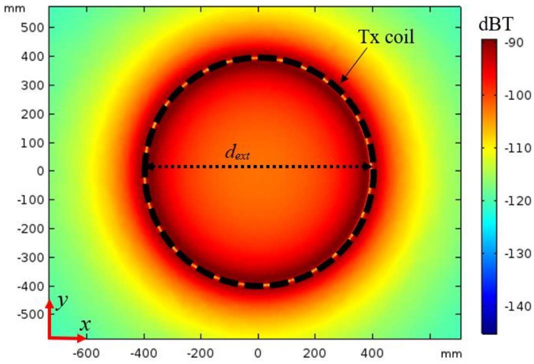


Fig. 7. Magnetic field map on a plane parallel to the primary coil at $h = 5$ cm.

IV. SYSTEM PERFORMANCE

The electrical performance of the system is evaluated in terms of efficiency. The equivalent circuit described in Section II.b is analyzed for different values of N_1 and for two different compensation topologies: series-series (SS) and series-parallel (SP). The value of the equivalent load resistance is obtained as $R_L = (V_{bat})^2/P_{ch} = 0.57\ \Omega$, considering a charging power $P_{ch} = 24$ W and a nominal battery voltage $V_{bat} = 3.7$ V. The calculated efficiency is shown in Fig. 8. The optimum number of turns for both SS and SP compensations is $N_{1opt} = 10$, but it is evident the convenience of the SS compensation topology in terms of efficiency that reaches $\eta_{max} = 89\%$. It should be noted that a higher number of turns could lead to a slight improvement of the efficiency, however it will increase the complexity of the coil. Finally, the efficiency of the system is calculated at any possible landing point of the drone in the ground pad. The results in terms of efficiency versus a possible lateral coil misalignment T_r up to a maximum of $T_{r,max} = 400$ mm are reported in Fig. 9. It should be noted that the efficiency increases for higher values of T_r since the magnetic field level is higher near the primary coil wire (see again Fig. 7). The obtained results show how the proposed WPT coil design is quite indifferent to a lateral misalignment due to imprecise landing of the drone, while it achieves a good WPT performance in terms of efficiency and power transfer.

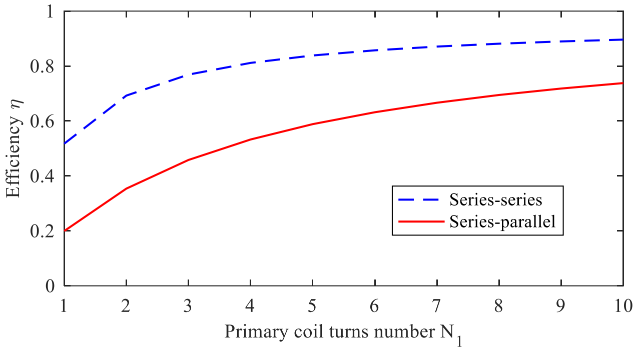


Fig. 8. System efficiency varying the number of turns N_1 and the compensation topology.

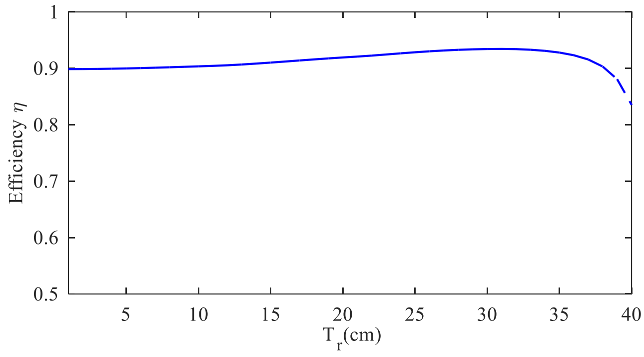


Fig. 9. System efficiency varying the misalignment T_r between the two coils.

V. CONCLUSIONS

An innovative, low cost, light solution is presented for the wireless charging system of a small UAV. The WPT system is based on resonant near field coupling. In the proposed approach a large primary coil is used to power the drone. On the receiving side on-board the drone a single-turn coil is adopted replacing the original propellers protection with an aluminum pipe that performs the double function of receiving coil and propellers protection. This approach ensures a high tolerance to coil misalignment condition and a significant reduction of the on-board components weight. The optimization of the primary coil in terms of number of turns and of the receiving coil in terms of the pipe dimension permits to obtain high values of efficiency. The general guidelines should be optimized for each case basing on drone characteristics and landing accuracy. The obtained results demonstrate a high tolerance of the proposed solution to lateral coil misalignment in combination with a high efficiency and a reduced weight of the on-board components.

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